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Manufacturing Methods and Technology

Computerized Production Process Planning

Final Report

August, 1977

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U.S. ARMY
MISSILE RESEARCH AND DEVELOPMENT COMMAND
REDSTONE ARSENAL, ALABAMA

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A computerized production process planning system was demonstrated. The system performs generative process planning for machined cylindrical parts. Manufacturer-independence is achieved by using process decision models that express local manufacturing practice. A man-machine communications interface permits human oversight/modification of process plan development. over

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20. ABSTRACT

Industry surveys were conducted to collect data relevant to the benefits of computerized process planning. Results of the surveys are summarized. Cash flow analyses estimating cost savings to industry are presented. Benefits of the demonstration system in defense procurement are projected.

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SUMMARY

Process planning is the activity which determines how a product is to be manufactured. There are several levels of process planning activity. Early in product engineering and development, process planning is responsible for determining the general methods of production. In the last stages of design, part design data is transferred from engineering to manufacturing and process planners develop the detail work package for fabricating the part.

Process planning is a major determinant of the cost of machined components. It determines the sequence of operations and utilization of machine tools. Cutting tools, fixtures, gages, and other accessory tools are specified. Dimensions and tolerances are determined for each stage of forming the workpiece. Feeds, speeds and other parameters of a metalcutting process are determined. Requirements for special processes, such as nitriding and plating, are determined and the production methods specified.

These activities of process planning are predominantly labor-intensive. Furthermore, process planners have varied skills and background and seldom will two planners produce the same process plan. Therefore, savings available through standardization and production cost analysis of the process are often forfeited. Industry has also observed in recent years a trend of less people available for process planning. Process planners are retiring from the field at a faster rate than people are being trained. This situation could endanger a manufacturer's ability to perform.

The above situation coupled with government and industry objectives to reduce costs or alternatively improve productivity has led to the widespread interest in computerized process planning. After several years of research and development activity, computer systems in process planning are beginning to emerge. Computerized Production Process Planning (CPPP) is such a system developed by United Technologies Research Center. The system assists process planners in planning the production of machined cylindrical parts. Through the use of automatic and semiautomatic means, CPPP generates a summary of operations and the detail operation sheets required by the workshop. Operation sheets include sketches of the fully dimensioned workpiece with tolerances. Machine tool, cut sequences, tools, and machining parameters are also specified.

CPPP is a first system aimed at developing an advanced technology to plan and control the cost of machined parts. The immediate objective has been to develop a system which will standardize the production process by automating the planning activities. It was also an objective to develop a system that could be used to analyze and evaluate process alternatives. Later enhancements

to the technology could provide for optimizing the process and would address noncylindrical parts as well as cylindrical parts. The basic concepts of CPPP are believed to apply in principle to all machined parts.

The program reported herein had three primary objectives:

- Describe the Computer Production Process Planning system technology.
- Demonstrate application of the technology for a cylindrical part family approved by the Army.
- Determine the benefits of computerized process planning in general and CPPP in particular.

CPPP Technology

Salient features of the CPPP technology are process decision modeling, geometric modeling, production cost and rate analysis, dimension and tolerance analysis, and man-machine communication. Process decision modeling is a technique developed by UTRC to specify the manufacturing rationale associated with the production of part families by a manufacturer. Process models are input to the data base and are used by CPPP to make decisions in generating sequences of operations. The models account for variances in part material, geometry and special process requirements. A computer process planning language called COPPL and a language processor were developed to support the implementation of process models. This provides the capability to implement CPPP in any manufacturing environment.

In addition to process models, the manufacturer must develop a large data base when implementing CPPP. Machine tool descriptions, types of cuts made by machines, cutter tools, stock removal and tolerance data, and machinability data are needed. Complete part design information must also be stored in the data base. CPPP requires information equivalent to the blueprint to generate a process plan. Material, shape, dimensions, tolerances, form conditions, surface finishes and special process requirements must be specified.

CPPP does not depend totally on automatic methods of generating process plans. An extensive man-machine interaction system can be used by process planners to review or modify process decisions made by CPPP. Metalcutting and nonmetalcutting operations and sequences can be defined. Also, detail operation data such as machine tools, cut sequences, tools, and feeds and speeds can be specified.

CPPP Demonstration

CPPP was developed and implemented as a demonstration system to show how a process planner working at a graphic display terminal would develop a process plan for a nitralloy sleeve. A process model and data base were developed for a part family of nitralloy sleeves manufactured by the Hamilton Standard Division of United Technologies Corporation. The family includes components of the JFC78 Fuel Control for the General Electric T700 engine, which was selected to power the Army UTTAS helicopter being developed by Sikorsky Aircraft. The demonstration part is made from AMS6470 bar stock and has requirements of nitriding to produce case hardness. The part family consists of parts with complex ID and OD geometry with cylindrical and noncylindrical features. Part sizes are up to six inches in length and diameters up to two inches. Surface finish requirements are very smooth and roundness, straightness, and taper form conditions are tight. The part family is of a complexity that manufactured components can require up to forty (40) operations.

The demonstration system shows that advanced computerized process planning is technologically feasible and the CPPP system can be implemented for any manufacturer of machined cylindrical parts. It also shows that CPPP reduces process planning labor and lead time, provides benefits of process plan standardization, and can be used to evaluate process alternatives. Also, it shows that process planners can effectively communicate with the computer to perform a variety of process planning activities.

Benefit Analysis

A benefit analysis of computerized process planning systems and CPPP, in particular, was performed. The analysis involved three steps. First, the benefits of computerized process planning to a broad spectrum of metalcutting industry were analyzed. Three different computer system capabilities were considered. An industry survey was used to collect data and sample opinion relevant to the benefits of each capability. The second step was a case study to estimate the benefits of the demonstrated CPPP system to the Hamilton Standard Division of United Technologies Corporation. Finally, the benefits of CPPP to defense industry were studied and the results used to estimate procurement cost savings by defense agencies. The impact on future procurement costs for missiles and other defense materials was estimated. As in the first step, a survey was used to develop expected benefits to defense industry.

The analyses show that computerized process planning offers substantial cost savings to industry and that defense agencies would benefit through reduced procurement costs. Cost savings in producing machined components will occur in process planning, workshop operations and tool costs. In addition,

there will be intangible benefits in lead time, machine utilization, production scheduling, and other areas. Net cost reductions of over 5% are expected from advanced process planning systems. A discounted cash flow analysis of the CPPP system yielded potential savings of $860 million in defense procurement for the period FY78 through FY87. If use of the system by 15% of defense industry is assumed, this translates into savings of $130 million.

PREFACE

The work reported herein was performed for the U. S. Army Missile Research and Development Command, Redstone Arsenal, Alabama, under Contract DAAK40-76-C-1104. The Missile Research and Development Command's technical representative was Richard A. Kotler. United Technologies Research Center (UTRC), East Hartford, Connecticut, was the prime contractor. IIT Research Institute (IITRI), Chicago, Illinois and the Hamilton Standard Division, United Technologies Corporation, Windsor Locks, Connecticut were subcontractors.

UTRC, the prime contractor, developed the description and demonstration of the CPPP system. In addition, UTRC provided data and estimates relevant to benefit analysis and participated in the case study of benefits reported in Section 3.2. Wilbur S. Mann, Chief, Computer Science Research, was Program Manager. The Principal Investigator was Mark S. Dunn, Jr.

IITRI performed the major portion of the benefit analyses presented in Sections 3.1 and 3.3. Hsien-Hwei Hunger Shu and John D. Meyer were IITRI's Principal Investigators.

Hamilton Standard provided data for the benefit analyses and the data base for the CPPP demonstration. Norman J. Ruel was Principal Investigator.

An Interim Report was submitted in November 1976. The large quantity of data and analyses given in Volumes II, III, and IV of the Interim Report are not reproduced here. Instead, a summary is included and those volumes are incorporated by reference into the Final Report.

ACKNOWLEDGMENTS

The contributions of several persons participating in this program are gratefully acknowledged.

Messrs. John D. Meyer, Hsien-Hwei H. Shu, Jack P. Kornfeld, C. Peter Grinstead, Henry M. Tockman and Charles A. Wells and Ms. Janis C. Church of the IIT Research Institute participated in the collection and analysis of benefit-related data. The major portion of the benefit analyses reported here were performed by them and other IITRI personnel.

Messrs. Norman J. Ruel and Robert A. Howe of Hamilton Standard collected information for the demonstration data base and participated in benefit analysis.

Messrs. William S. Strickland, Robert T. Leo, and Darryl E. Parsley played important roles in developing the CPPP demonstration.

Special thanks are due to the companies which provided data for benefit analyses. These are listed in Tables 3 and 15.

Mr. Richard A. Kotler, the U.S. Army Missile Research and Development Command's Technical Representative, provided valuable guidance to the program.

Computerized Production Process Planning

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1.0 INTRODUCTION

Process planning is the first step in manufacturing. The activity has a major effect on the cost of fabricating goods in the metalcutting industry. It affects production planning, machine utilization, tooling requirements, machining efficiency and other determinants of cost. A large portion of the widespread interest in Computer-Aided Manufacturing has, therefore, been focused on computerized production process planning (CPPP). After a decade of research and development activity, operational CPPP systems are beginning to emerge.

The program discussed in this report had three objectives.

1. Describe the CPPP system technology.

2. Demonstrate application of the technology.

3. Determine benefits of computerized process planning in general and the demonstration system in particular.

The introductory discussion below provides general background material and identifies the objectives that have guided UTRC's approach to a CPPP technology. The method of approach to benefit analysis is also presented.

1.1 General Background

Interest in programming computers to generate process plans for manufacturing parts is world wide and involves private industry, universities, and governments. In recent years the interest has intensified due to an increasing awareness of what computers can do for labor-intensive methods of process planning and manufacturing in general. Process planning procedures that depend exclusively on skilled or trained production labor are vulnerable to delays, errors, and higher-than-necessary production costs. Dependence on such methods often precludes a thorough analysis and optimization of the process plan and nearly always results in the nonstandardization of processes.

Unfortunately, the complexity of machined parts process planning has resulted in computerized process planning remaining in the conceptual stage for some time. The benefits are anticipated, but the path to follow has been unclear. UTRC presents its CPPP technology as one possible path and hopes in doing so to be making a significant start toward Automated Process Planning.

There have been several notable projects in computerized process planning since the late 1960's. Much of the early work originated in Sweden, Norway, and Germany. In general, these systems, such as SINTEF's AUTOPROS and systems

developed by Aachen University, contributed significantly to the present level of understanding, but proved to be too limited in scope. Other projects like EXAPT and GETURN were also of interest, but they primarily provided detailing of numerical control operations after much of the required process planning was finished. In the United States, much of the current work is directed toward the development of data processing systems capable of storing and retrieving process plans by coded methods. Although these systems offer benefits of standardization, they do not address the problems of generating process plans or economic analysis of the process.

In general, the technology of computer process planning can be characterized by differentiating between the basic technical approaches that have been advocated. The highest level of differentiation divides the technology into the "variants" and "generative" principles. The first is based on storing standard process plans in the computer for specified families of parts. Using a part classification coding technique, process plans can be retrieved and varied for a new part. This approach partially automates the conventional procedure of using an existing process plan to produce a new plan. The concept is based on similarity of fabricated components. The CAPP system being developed by CAM-I is a system based on the variants principle.

The generative approach is more complex because the computer must be capable of making process decisions. The idea is to provide enough intelligence about metalworking to allow the computer to generate a sequence of operations and detailed operation plans. This kind of system requires detailed input about the part design. From this input, the generative system determines the sequence of stock removal operations; selects machine tools, cutting sequences and cutter tools; and determines machining parameters of feed, speed and depth of cut. Additionally, generative systems provide some optimization of the process plan by basing decisions on the analysis of production cost and/or rate.

A basic problem in developing generative systems is the formulation and programming of manufacturing rationale and data reflecting sound metalworking principles. This has led to two basic technical approaches. One school of thought advocates a "backward planning" technique whereby the computer looks at the finished part specification and works backward, determining for each surface requirements for finishing, semifinishing and roughing operations. The second school of thought advocates a "foreward planning" technique whereby the computer begins with a finished part and raw material description and works forward producing roughing and semifinishing operations before finishing operations. Both of these approaches have certain advantages.

1.2 CPPP Technology Objectives

UTRC initiated its research of computerized process planning technology in 1973 with several objectives. First, the computer system developed must be adaptable to any manufacturer of machined parts. This meant that the system should generate process plans based on the manufacturing methods of a particular workshop. Thus, a method had to be developed to formulate and input to the computer system the rationale for making process decisions in accordance with a manufacturer's resources.

The purely generative approach to computerized process planning appeared to be a capability that would not be developed for many years. The major obstacle is the difficulty to capture and organize every bit of manufacturing logic that might ever apply. Therefore, the best plan of attack was to evolve the technology toward the goal of a generative system. Thus, UTRC's plan was to include characteristics of both the variants and generative systems. Manufacturers would be required to formulate "models" of manufacturing rationale to produce a sequence of operations. Each model would be for a family of parts. A model would allow CPPP to automatically determine the set of operations needed to fabricate a particular part and determine the part surfaces involved in each operation.

Although this approach was not considered trivial, it appeared to be naturally aligned with the process planner's way of thinking about his work. It also would allow each workshop to specify its own way of doing business. A manufacturer would be able to define standard sets of operations augmented by the rationale that specifies when an operation is required. This approach could also be used to develop highly sophisticated models of manufacturing rationale covering a large variance of part material, geometry and processes. The actual process plan would be determined solely by the design specifications of a part.

UTRC also believed that a CPPP system should be capable of generating alternative solutions to a process problem and then pick the best. This is based on the fact that there is not a unique solution to how a part can be fabricated. The sequence of operations, machine tools, cut sequences, type of cutting tools, and machining parameters can all vary. It was decided that a detail analysis of production time and cost would provide the numerical criterion for selecting the best process.

UTRC also believed it important that full part design information be available to the system. This would make it possible to base decisions on precise part characteristics, rather than on codings of general part features. It would also allow for full analysis of dimensions and tolerances and the generation of workpiece sketches with operation sheets.

UTRC also felt strongly that totally deterministic systems would not be developed for a long time. There would always be situations where manufacturing would want to influence or change computer decisions or provide data that is missing in the system. Therefore, an extensive man-machine interaction capability had to be developed.

Based on the above beliefs, UTRC's chosen approach to CPPP centered around the following specific technological problems:

1. Define an Analytical Framework for Generating Process Plans - The generation of a process plan for fabricating a machined part requires that a large multidimensional problem be solved. Processes, machines, cutting sequences, tools and machining parameters must be chosen to minimize production cost and/or rate. The situation exists where alternative solutions must be examined and evaluated before a "best" solution can be determined.

2. Model Manufacturing Rationale to Create the Sequence of Operations - A standard method of modeling manufacturing rationale for making process decisions in a computer must be developed. The method should provide the capability to determine requirements for metalcutting and special processes (heat treatment, plating, etc.) needed to transform a raw material to a finished part.

3. Select Machine Tools - A method of selecting machine tools for metalcutting operations must be formulated and integrated into the overall analytical framework for generating process plans.

4. Select Cut Sequences and Cutter Tools - A method of selecting cutting sequences and tools for an operation must be formulated and integrated into the overall analytical framework for generating process plans. Theoretically, several cutter tools may qualify for each cut in an operation. Therefore, a method of solution must be developed that identifies the type of cuts in an operation and then determines the best tools from a set of alternatives.

5. Select Feeds, Speeds and Depth of Cut - A method of determining the feed, speed and depth of cut for a given cutting situation must be formulated and integrated into the overall analytical framework for generating process plans. The method should include table look-up and mathematical models.

6. Calculate Dimensions and Tolerances - To generate a detailed process plan for a machined part, the computer system will be required to calculate the dimensions associated with every cut in the process. Therefore, a general method of calculating dimensions and tolerances must be formulated and integrated into the overall analytical framework for generating process plans.

7. Produce Process Plan Documents - The system must be capable of producing operation summary data (sequence of operations) and detailed operation data identifying specific cut sequences, tools, machining data, dimensions and tolerances. It should also generate dimensioned views of the workpiece for different operations.

8. Provide Description of Part Design - Data describing the part design must provide the equivalent information content of the blueprint. Therefore, a method must be developed to model the part geometry and its physical attributes.

9. Provide Man-Machine Communication Interface - A standard method of allowing a process planner to interact with the computerized process planning system should be developed. The communication interface design must be easy to use, be flexible and provide the planner with the maximum opportunity to interact with all decision-making and analysis functions.

10. Determine Time/Cost Standards - Advanced planning systems will be developed to make many decisions based on the analysis of production costs and rates. Thus, a method is needed to calculate time/cost standards based on normal industrial engineering practice.

1.3 Method of Approach to Benefit Analysis

There is widespread feeling in industry, government, and research institutions that computerized process planning offers large cost savings. To date, however, there has been no significant effort to quantify these benefits. A major objective of the subject program was to develop an economic analysis of computerized process planning.

Benefit analysis was approached as three tasks:

1. Analysis of benefits of computerized process planning for a broad spectrum of industry.

2. A case study analyzing benefits of the demonstration CPPP system for the Hamilton Standard Division of United Technologies Corporation.

3. Analysis of benefits of the demonstration CPPP to industry supplying Army missile components and other defense items. Extension of that analysis to estimate cost savings to government agencies.

To estimate benefits for a broad spectrum of industry, a survey was sent to a large variety of manufacturers. The survey requested data on machining operations and costs. It described three process planning systems and asked for estimated costs and savings for each. The responses to the survey were used to define analysis cases and to set input parameters for a discounted cash flow analysis of each case for each system.

Having participated in CPPP development since 1974, Hamilton Standard has developed the manufacturing data and familiarity with CPPP needed for benefit analysis. In analyzing savings and costs for Hamilton Standard, CPPP's capabilities were evaluated with respect to manufacturing costs for process planning labor, machining labor, and consumable tooling. Implementation costs and recurring costs due to CPPP were estimated. The analysis was performed for two CPPP capabilities -- the basic system described in this report and a more advanced capability to be developed in the future.

In the third task, a survey was mailed to a large number of companies supplying machined parts to the Department of Defense. The survey described CPPP's capabilities and requested estimates of costs and savings. Again, survey results were used to determine inputs for a discounted cash flow analysis for several parametrically-defined cases. Using procurement estimates, the benefits to individual companies were then translated into projected savings for the Missile Command, the Army, and the Department of Defense.

The preliminary nature of the benefit analysis reported herein must be emphasized. Two of the three analysis tasks depend on survey responses. The number of responses was not sufficient for statistical validity. The respondents' familiarity with the technology was uncertain. It was not feasible to perform the group communication and iteration needed to reach consensus. The Hamilton Standard analysis is dependent on local manufacturing parameters. While the analysis would yield similar results for some other companies, greatly different results would be obtained for others. Finally, it should be noted that the judgment of the contract team was necessarily applied in each of the analyses.

Despite the observations above, the work reported here is felt to be an important advance in the economic assessment of CPPP. The surveys yielded the first known compilation of industry opinion on benefits. The analyses are valuable as a preliminary quantification of CPPP benefits and also exhibit a methodology for future analysis.

Volumes II, III and IV of the Interim Report present the benefit analysis for general industry. Data and calculations are given in detail. The contents of these volumes are summarized, but not reported in detail, in this final Report. All data and calculations for the Hamilton Standard study and the Department of Defense benefit analysis are presented herein.

2.0 CPPP TECHNOLOGY

Computerized Production Process Planning (CPPP) is a system to assist process planners in planning the fabrication of machined cylindrical parts. This would include parts with cylindrical features for which turning, drilling, grinding, honing or lapping operations are required. The system also provides assistance in planning cylindrical parts with requirements to machine non-cylindrical features such as flats, windows, slots and lugs. Requirements for milling operations, or others such as EDM, would be identified and their operations included in the summary of operations. Unlike the detail planning technology available for cylindrical features, however, CPPP will not plan operation details for non-cylindrical features. CPPP can also identify requirements for non-metalcutting operations such as deburring, stress relief, heat treatment, nitriding, inspection and others.

The selection of machine tools, cut sequences, cutting tools, feeds, speeds, and cutting depths is a complex problem. CPPP attacks the problem by evaluating alternative combinations for each operation and then selects the best based on production cost or rate. The demonstration system has the analytical framework for doing the required analysis. Modules are included for each problem area.

A salient characteristic of CPPP is its adaptability to different manufacturing environments engaged in metal removal. This has been achieved through the unique method of "process decision modeling". This method allows a manufacturer to define and program the process rationale for fabricating parts of certain design characteristics. The process models are added to the CPPP system through the data base. This procedure results in extending the basic CPPP system with the workshop-dependent methods of the manufacturing firm. Figure 1 illustrates the concept.

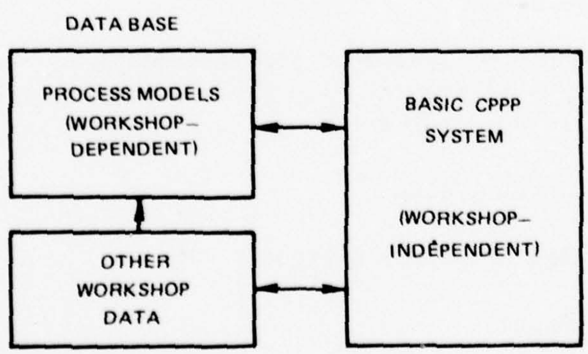

FIGURE 1 . CPPP IMPLEMENTATION CONCEPT

When activated by CPPP, a process model would make decisions of what, when, and how (type of operation) part surfaces are cut. In addition, the model would determine requirements for non-metalcutting operations. This results in fully describing the transformation of a raw material to the finished part.

Implied in the above is a second salient characteristic of CPPP -- the use of geometric modeling and full design information. Process models are dependent on interpreting the design and special process specifications of a part. Based on this data, requirements for rough, semifinish and finish operations and special processes are determined for each part surface.

A third characteristic of CPPP is the extensive man-machine communication capability. The process planner, using a graphic display terminal, can choose among many levels of involvement in CPPP processing. He can choose to review and perhaps modify every CPPP decision, he can opt for fully automatic planning, or he can select some intermediate level of operation. This capability eliminates the sole reliance on process models for producing process plans.

Although the CPPP system has been developed for machined cylindrical parts, the concepts apply in principle to all machined parts.

The first section below provides an overview of the CPPP system. The software components, the process planning functions, and the hardware are discussed. Data base requirements and input and output are included in the discussion of software components. Following the overview, subsequent sections discuss the technical concepts associated with planning a sequence of operations, planning operation details, calculating dimensions and tolerances, and man-machine communications.

2.1 System Overview

2.1.1 Software Components

CPPP is an integrated system of software modules. A high-level diagram of the system is shown in Figure 2. There are seven principal components, each of which is discussed below:

- The Data Input System
- The Language Processor System
- The Data Base
- The Process Decision and Analysis System

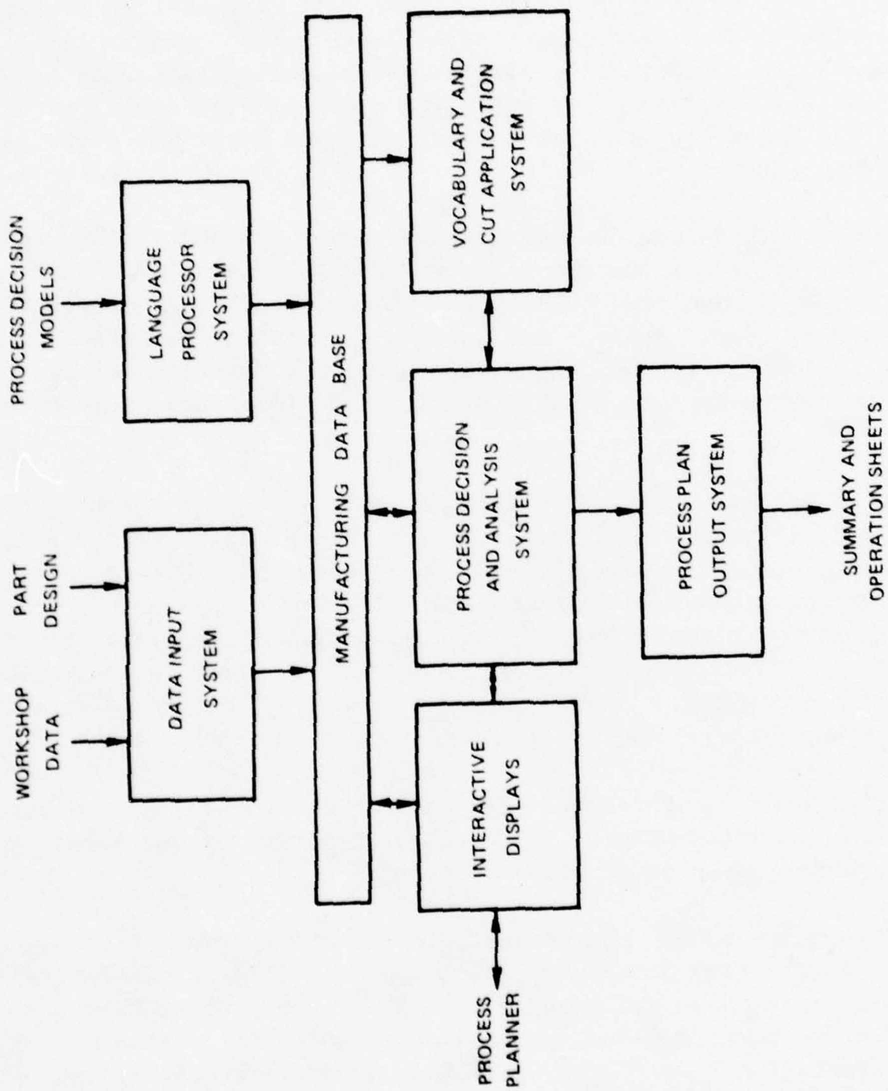

FIGURE 2. CPPP SOFTWARE COMPONENTS

- The Vocabulary and Cut Application System
- The Interactive Display System
- The Process Plan Output System

The data input and language processor systems provide a manufacturer with the means to build the large data base required by CPPP. A detail description of the data base is provided in Appendix C. The data base must be developed to contain descriptions of the workshop's machine and tool resources, stock removal allowances for cutting materials, tolerance information with respect to cutting situations, machinability information and process decision models. To use CPPP, it is also required that process planners first enter the part design into the data base.

CPPP requires part design data equivalent to the information content of a blueprint. Figure 3 shows the level of data description required. It includes part shape, dimensions, tolerances, surface finish, geometric form conditions, material specifications and any requirements of surface treatment or coatings. In addition to the part design data, the raw material (bar, casting, forging, extrusion) to be used must be identified and geometrically described.

The language processor system is used to input to the system the process decision models of different part families. Process planners will use the computer process planning language (COPPL), developed under the contract, to program the logic of process decision models. The programmed models are converted into a computer readable code by the language processor and then stored in the data base. Process planners using the COPPL language do not require computer programming skills. The language is more of an English-like language than a computer programming language. This has resulted from the objective to develop COPPL so that it could be used to document or newly specify a manufacturer's process rules. Therefore, the language can be easily read and understood by manufacturing people. A detail description of the process planning language and processor is provided in Appendix D.

The COPPL language allows the process planner the freedom of choosing vocabulary when formulating process decision models. This eliminates restrictions on the process planner and provides the flexibility to express the rationale for fabricating part families. For example, the process planner can use terms like the following: deep hole, free end, open diameter, exposed, counterbore, groove, chamfer, true position, diametral tolerance, surface finish, etc. When these terms are used in programmed expressions of a process model, such as:

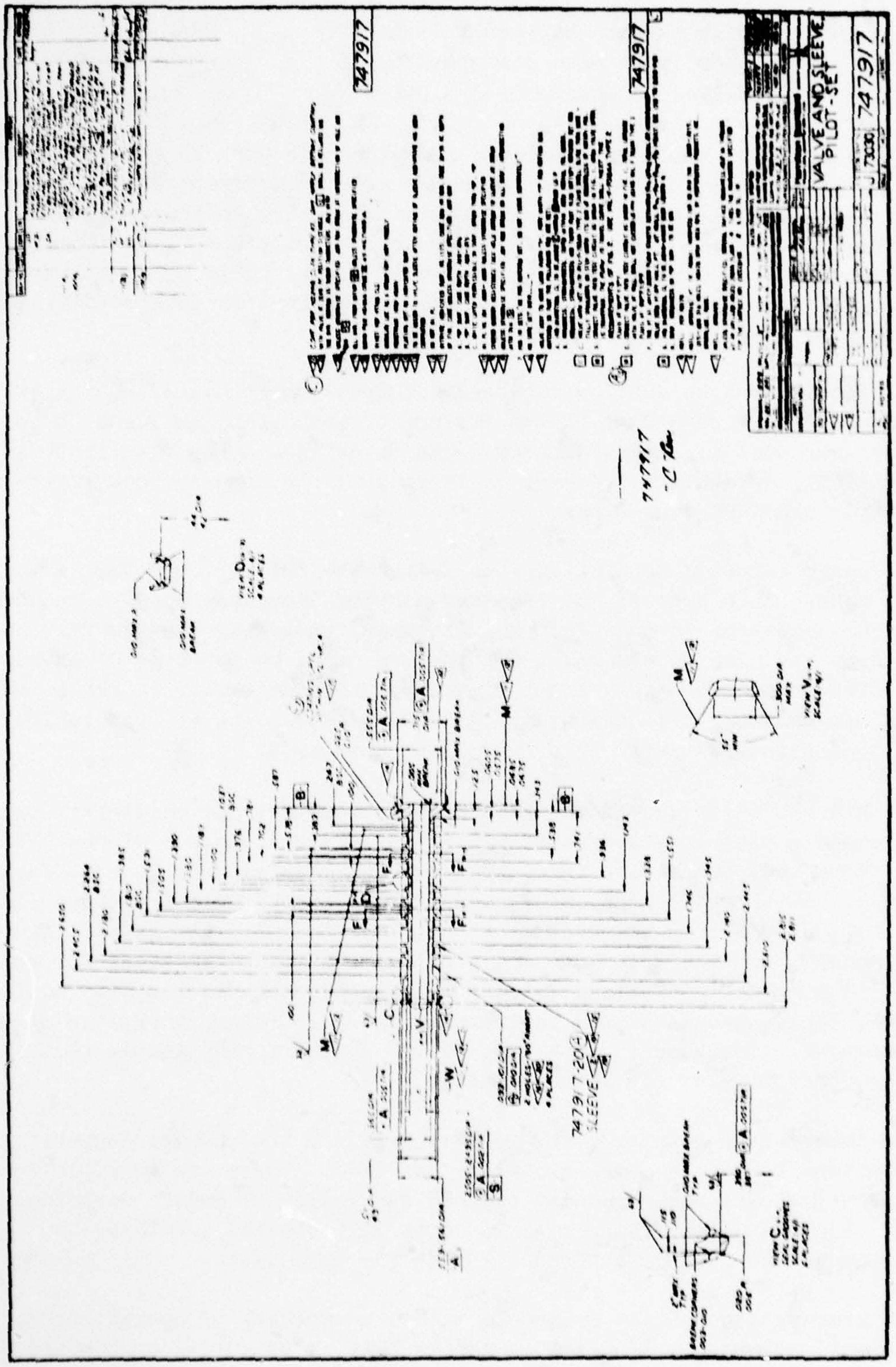

FIGURE 3 . DESIGN DATA AS GIVEN BY BLUEPRINT

Turn outside surface on manual lathe if
surface is an open diameter, (and)
diametral tolerance is ≥ 0.002 $

they have a specific meaning. A simple computer code must be written for each vocabulary term so that CPPP can interpret the programmed expression. These computer codes are easily added to the CPPP system through the vocabulary and cut application system. In the above example, the code for "open diameter" would test a part surface description to determine if it is an open diameter. A detail description of vocabulary programs implemented for the demonstration part family is provided in Appendix F.

The requirement to develop vocabulary codes reduces significantly after process models have been implemented for one or more part families. Much of the vocabulary used by a manufacturer would be defined after the first few part families. Vocabulary programs could also be standardized and implemented for multiple manufacturing firms.

CPPP also allows a manufacturer to define the type of cuts that a machine tool can make. Each type of cut requires a simple computer code to be added to the CPPP system as is done for the vocabulary programs. In general, the type of cuts that can be made by a machine are based on the type of machine tool. If the same cut can be made on multiple machine tools, it can be indicated in the machine tool data base. A detail description of cuts implemented for the demonstration system is provided in Appendix G.

The process decision and analysis system, the interactive display system and the process plan output system combine to form the nucleus of the CPPP system. These components are independent of any manufacturer or part families. The process decision and analysis system is the "heart" of the process planning capability. It contains the modules to retrieve the part design data and the process models from the data base and provides the main subsystems for generating the sequence of operations, planning operation details (machine tools, cut sequences, tools, and machining parameters) and calculating workpiece dimensions and tolerances. Included in this part of the system is the module that interprets the coded form of the process model.

The interactive display system consists of all the modules supporting communications between a process planner and CPPP. There are multiple interaction points at which the process planner can review or modify decisions made by CPPP. Additionally, displays are used to initiate and terminate the CPPP system and to provide information from the data base.

The process plan output system produces the summary of operations and detail operation sheets. In each case, the data is output in a standard form. It would be a simple matter to reformat the data if a manufacturer desired a different form of the output. Figures 4 and 5 respectively show the summary

UTRC CMPP SYSTEM SUMMARY OF OPERATIONS COMPUTER GENERATED

PART NO: 728149-10 E.C. NO: A REV. NO: 7 DATE: 7-10-76 SHEET 01 OF 01
PART NAME: CONTROL VALVE PISTON MODEL: EVC-3 AREA: KTG PLANNER: S.PFLEDERER
RAW MAT'L: AMS 5630 STAIN. STEEL HARDNESS: 20-30 RC , 1.875 BAR LOT SIZE: 150 GROUP:

DEPT	MACHINE	TYPE OF MACHINE	OPERATION DESCRIPTION	OPER	PRERED	T/K	SETUP	CYCLE	RECORD OF REVISIONS
101	6010	BENCH	DRAW MATERIAL	010					
3F	2515	CENTERLESS GRINDER	GRIND O.D.	020					
3F	3523	GES NO.4 ABM	BLANK PART	030					
27	2700	FURNACE	STRESS RELIEVE	040					
203	3321	JEL PFM MOD 6 LATHE	FACE AND TURN	050					
203	0288	DE HOFF 2 SPINDLE	GUN DRILL 1 HOLE	060					
203	3321	JEL PFM MOD 6 LATHE	CENTER	070					
203	2534	CINN 2 C'LESS GRIND	GRIND O.D.	080					
203	2506	VAN NORMAN C'LESS	CRUSH GRIND FORM	090					
203	0630	VIBRATORY TUB	DEBURR	100					
203	0954	DRILL PRESS	DRILL 1 HOLE	110					
203	0600	BENCH	BURR HOLE	120					
27	2700	FURNACE	HEAT TREAT	130					
203	2842	X-LO CENTER LAP	LAP CENTERS	140					
27	4810	TANKS	PASSIVATE	150					
207	7560	TANKS	FLUOR. PENETRANT INSP.	160					
203	3900	BENCH	MARK IDENT, TAG	170					
207	7020	BENCH	FINAL INSP, PRESERVE, FIN STORES	180					

FIGURE 4 . SUMMARY OF OPERATIONS

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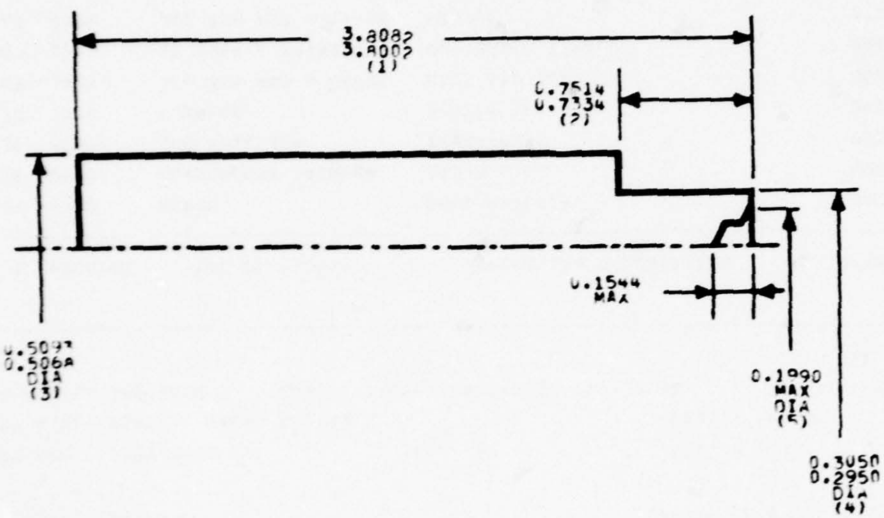
UTRC CMPP SYSTEM — OPERATION SHEET — COMPUTER GENERATED

PART NAME: CONTROL VALVE PISTON   MODEL: EVC-3   OPER: 030   AREA: 3F   PART NO: 728149-10
MACHINE: BES NO.4 ABM   MATERIAL: AMS 5630   STAIN. STEEL   SHEET 01 OF 02
OPERATION: BLANK PART   PLANNER: S.PFLEDERER   DATE: 7-10-76
APPROVED: DATE:



REF	CUT TYPE	SPEED RPM	FEED IPR	NO. CUTS	SURFACES CUT
A	OPEN TURN	100	.020	1	3
B	FACE END	100	.010	1	
C	TURN STEP	150	.020	2	2 4
D	CENTER	120	.015	1	5
E	CUTOFF	75	.007	1	

RECORD OF CHANGES

FIGURE 5. DETAILED OPERATION SHEET. (Continued on next page)

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UTRC CMPP SYSTEM                         OPERATION SHEET                              COMPUTER GENERATED

PART NAME: CONTROL VALVE PISTON     MODEL:     EVC-3        OPER:  030      AREA:   3F        PART NO: 72814[illegible]
MACHINE:   BES NO.4 ABM             MATERIAL: AMS 5630    STAIN, STEEL                            SHEET 02 OF 02
------------------------------------------------------------------------------------------------------------

                REF    TOOL        TOOL NO.                                REF    TOOL       TOOL NO.
                ---  --------  ----------------                            ---  --------  ---------------
                 A    CUTTER    SC0465-T-10
                 B    INSERT    MS201-6
                      HOLDER    CS876-2
                      CBIPBRKR  CS301-2
                 C    CUTTER    561505-T-3
                 D    DRILL     CS136-85
                 E    CUTTER    CS636-13

                                                                                RECORD OF CHANGES
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FIGURE 5. DETAILED OPERATION SHEET. (Concluded)

of operations and operation sheets. The former provides general part information at the top of the page and then lists specific information for each operation: operation number and description, machine tool, department, setup and cycle time, etc. The detail operation sheet provides general operation data at the top and then identifies the sequence of cuts, feeds and speeds and tools required. The operation sheet also provides a dimensioned sketch of the workpiece as it would look following the operation. Dimensions and tolerances are given for each cut.

2.1.2 Process Planning Functions

Figure 6 shows a high-level view of the three primary process planning functions of CPPP. They are organized to produce a process plan in three distinct and separate steps. The first step generates the sequence of operations. It begins when the process planner inputs a part number to the system. The part number is used to retrieve the design data from the data base. The raw material description specified by the manufacturer for the process would also be retrieved with the part design data. CPPP does not select the raw material; the requirement must be determined outside the system and identified in the data base. Also contained in the design data is a classification code identifying the part family to which the part belongs. This code is used to retrieve the appropriate process model from the data base. The code can be designed to provide any level of classification desired by the manufacturer. In the demonstration system, part families are primarily broken down by function, e.g., compressor seals, valves, sleeves.

The sequence of operations is generated with the process model alone or by a combination of the model and process planner interacting with the system. The model is programmed to determine a sequence of operations based on specific geometry and material characteristics found in the part design data. The generated sequence would contain both metalcutting and non-metalcutting operations. Additionally, the specific part surfaces or features cut in an operation would be identified. Also, part surfaces requiring special processes such as nitriding or plating would be identified with the operation. This planning function is defined in greater detail in Section 2.2.

Results of the initial planning function are stored in the data base in the form of an operation matrix. The matrix is organized so that complete summary information is known about any operation or part surface. The data is used by subsequent planning functions to determine what the workpiece should look like after each operation. For example, the matrix specifies for each part surface the types of operations required to transform the raw material to a finished part.

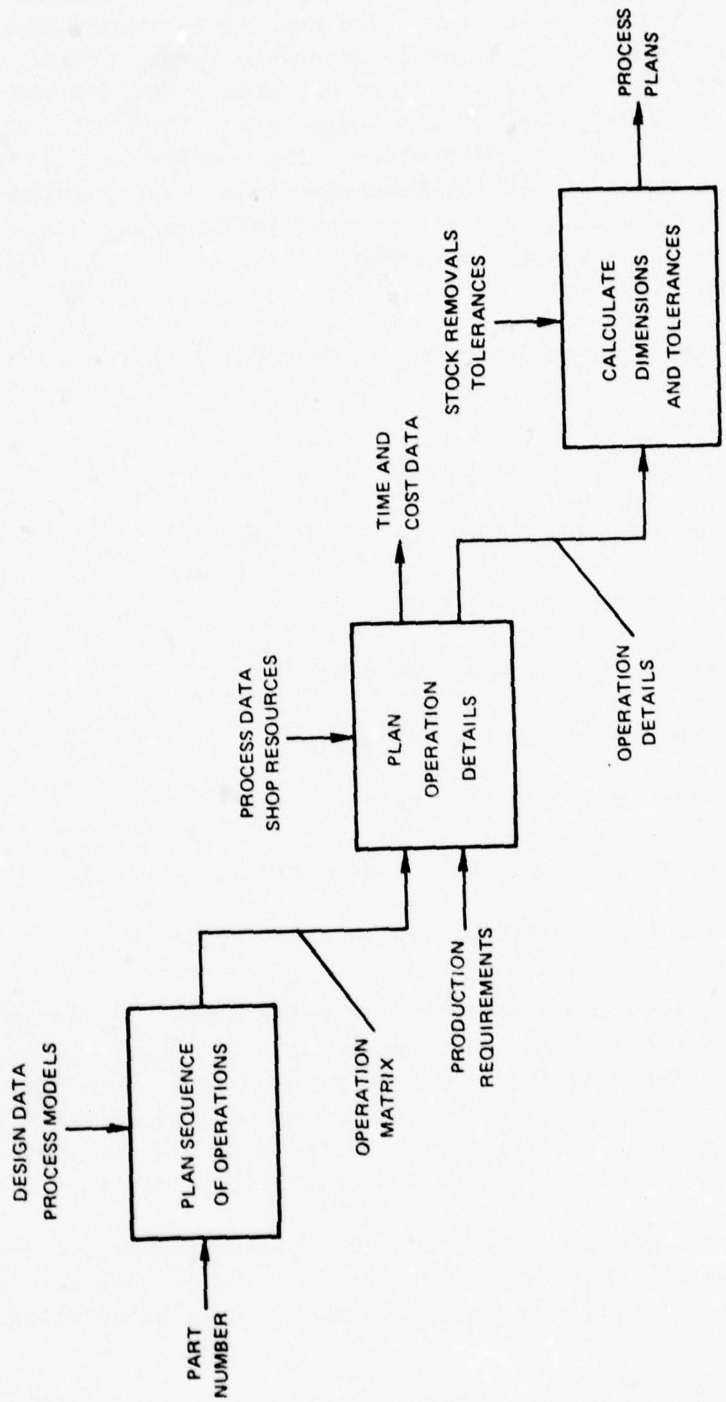


FIGURE 6. PROCESS PLANNING FUNCTIONS

The second planning function will generate the details of each operation defined in the operation matrix. The task is to select machine tools, cut sequences, and cutter tools and to determine feeds, speeds, cutting depths, and number of cutting passes. There are many variables and interdependencies in making detail decisions of the above type. Therefore, an analysis procedure has been developed to evaluate alternative combinations of machine tools, cut sequences and cutter tools for each operation. The best combination is chosen based on optimum production rate or cost performance. As in the first planning function, the process planner has the option to interact with CPPP to review or modify decisions made.

The detail planning function is factored into the subfunctions identified below:

- Determine candidate machine tools
- Determine candidate cut sequences
- Determine types of cuts
- Select candidate cutter tools
- Determine machining parameters
- Determine production rates and costs
- Select best combination of tools
- Select best machine tool and cut sequence

These subfunctions are described in greater detail in Section 2.3. The manufacturer must provide several kinds of data to support planning of operation details. The data required includes machine tool descriptions, the types of cuts made by machines, stock removal allowances, preassigned cutter tools, and machinability data. Additionally, the process planner must specify the approximate lot size and production criterion to use in the analysis.

The output generated by the detail planning function consists of detailed operation descriptions and production time and cost data. The operation data is stored in the data base for subsequent use in calculating dimensions and tolerances.

The third planning function calculates the actual workpiece dimensions and tolerances for each operation. Prior to this step the system works only with nominal values. Therefore, this function also serves to ensure the part

can be made within tolerance by the process plan. A salient characteristic of this function is the use of tolerance chart procedures for analyzing tolerance buildup and calculating dimensions. To do the analysis and calculations, the manufacturer must provide stock removal allowances and tolerance data. The output produced is used to generate operation sheets with dimensioned workpiece sketches. This function is described in greater detail in Section 2.4.

2.1.3 Hardware

The hardware required by the CPPP system consists of a general purpose computer with common peripheral devices, a graphic display terminal, and a hard copy line plotting device.

The CPPP system was developed on a general purpose computer of the UNIVAC 1108/1110 class. Modification for use on such general purpose computers as the IBM 360 and 370 models can be accomplished with relatively little effort.

As currently segmented, CPPP requires about 60,000 words of computer memory. This requirement can be reduced or increased by varying the software organization. The computer memory requirement is somewhat dependent on the complexity of the process planning problems to which the system is applied. Complex part families and process plans require more memory than simpler ones.

Disks or other direct access devices are required to store the CPPP system and the manufacturing data base. The system itself requires about 550,000 words, if source (symbolic) and object (relocatable) code are stored. If only the load module (absolute code) is stored, about 60,000 words suffice. Storage requirements for the manufacturing data base will, of course, vary widely. The smallest viable data base will require a few hundred thousand words while very large manufacturers will require millions. It would be practical to use magnetic tape, rather than direct access storage, for roughly half of the data base.

The CPPP user interacts with the system via a low cost graphic display terminal. The system has been implemented for TEKTRONIX 4006, 4010, 4012, and 4014 terminals with 021-0074-00 Optional Data Communications Interface or its equivalent. A full duplex transmission rate of at least 1200 characters per second is recommended. (Slower rates may be used, but noticeably degrade system performance.) Software support is the TEKTRONIX PLOT-10 Terminal Control System and Standard FORTRAN Subroutine Package.

A line plotter is used to generate workpiece sketches for hard copy process plans. CPPP currently uses a CalComp plotter with a local software package. Conversion to use other line plotters and/or software packages can generally be accomplished with little effort.

2.2 Plan Sequence of Operations

To develop a sequence of operations for a machined part, a process planner would consider the part shape, dimensions, tolerances, finish and material requirements, and special process requirements. Generally speaking, the process planner prepares himself for the task by organizing his thinking in accordance with some key characteristics of the part to be fabricated. For example: the part is cylindrical and is made from bar stock of AMS 5630; it has a thru bore; L/D is less than 2.0; tolerance requirements are less than .001; surface finish requirements are less than 16; etc. Based on such information, the planner calls on his experience to formulate an overall production approach. CPPP provides a similar approach to generate process plans.

2.2.1 The Properties of a Process Model

The CPPP system allows a manufacturer to specify to the computer the rationale for planning the fabrication of a part. The method used is called process decision modeling. The function of a process model is to determine for a specific part the requirements for (1) metalcutting and non-metalcutting operations, (2) operation sequence, (3) types of machines (or specific machine tools), (4) specific part surfaces cut by metalcutting operations, and (5) special processes.

Figure 7 shows the kind of operation data that would be generated by a process model. The number of the operation in the sequence, the operation description and the type of machine tool are determined for each operation. In the example, operation 0010 is a turn and face operation on an automatic bar machine. CPPP would determine the best bar machine to use when planning the operation details. Operation 0020, however, shows that the W&S 2AC (automatic chucker) is to be used. This illustrates that process models can call out specific machine tools for an operation. Figure 7 also shows another important characteristic of process models -- they identify the specific part surfaces machined in a metalcutting operation or affected by special processes. The heavy lines show the affected surfaces in each operation. With this information, CPPP determines the geometry of the stock removal in the operation. This data is required when planning the details of stock removal.

Figure 8 shows the kind of operation data that will be known about each part surface following the planning of a sequence of operations. View A shows that the counterbore requires a total of five operations to achieve blueprint conditions. The rationale for each of these operations is given in the process model. For example, a final lap operation is required for bores whenever surface finish is 8 or less, diametral tolerance is tighter than .0004, or form conditions, such as straightness or roundness, are less than .0002. If blueprint conditions for the counterbore were not as tight, then the grind

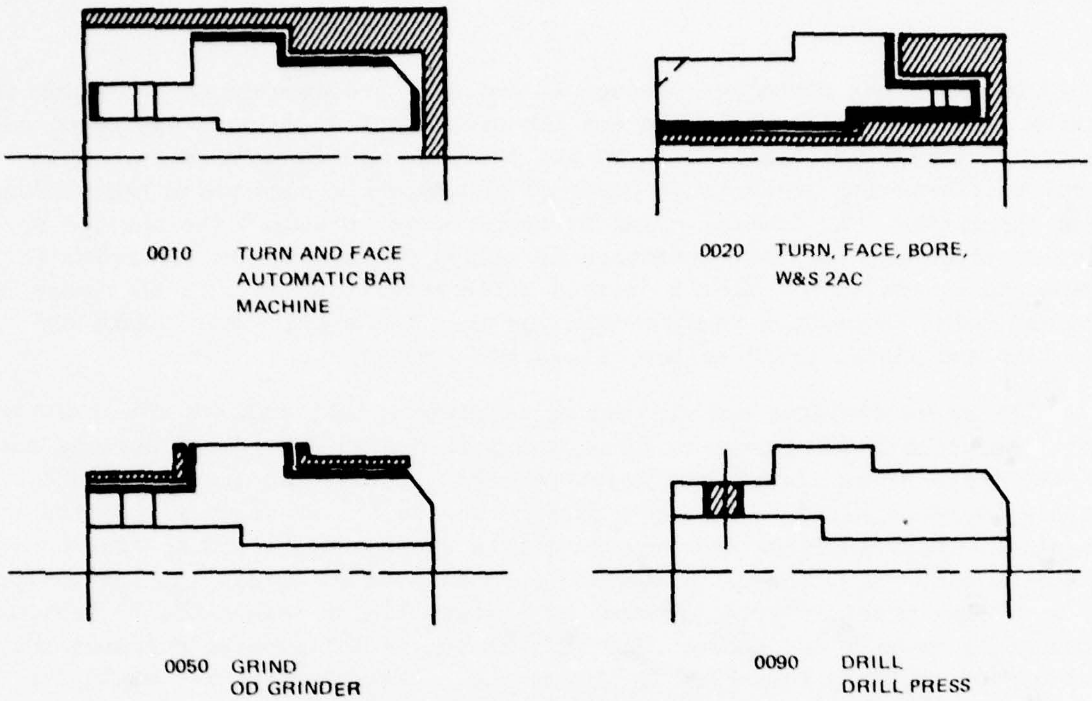


FIGURE 7. TYPE OF METALCUTTING OPERATION DATA GENERATED WHEN PLANNING SEQUENCE OF OPERATIONS. Heavy lines identify the surfaces cut in an operation.

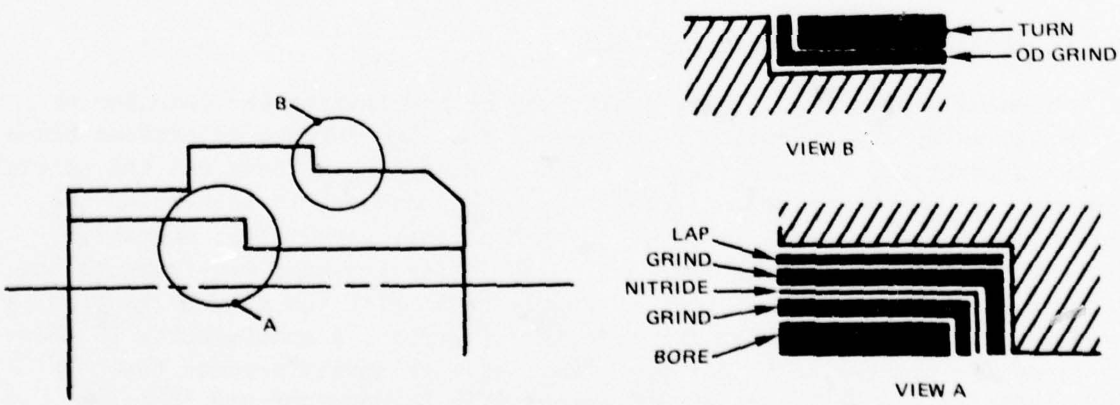


FIGURE 8. EXAMPLE OF OPERATION DATA THAT IS GENERATED FOR EACH PART SURFACE WHEN PLANNING SEQUENCE OF OPERATIONS

could be the final operation because ID grinders are capable of producing the finish condition. The rationale for the second grind includes the requirement to remove the "white layer" left by the previous nitriding process. This results in removing the outside layer of the hardened case which has poor surface integrity. The initial grind is required to "prepare" the surface for the nitride process. The bore operation is called out by the process model to shape the counterbore. View B shows a different situation. In this case the process model recognizes requirements for only two operations: shape the shoulder and finish grind to meet blueprint conditions.

The above examples and discussion illustrate that process models determine operation requirements based on the part design specifications and the capabilities of available production methods. In one case, grinding and lapping were required to finish a surface and in the other only grinding was required. Some surfaces may require only a turning operation to finish. Figure 9 shows the kind of data that is considered in developing the rationale of a process model. Typical ranges of surface finish obtainable by various production methods are shown. The information is for general guidance only because of the many variables in processing. Each manufacturer would incorporate into its models the knowledge of surface finish ranges for its own workshop. The ability of production machines to hold tolerances under certain conditions is another example of information considered in the formulation of process models. Requirements for special processes, such as nitriding, are determined simply by the specification called out in the blueprint.

A process model would also include rationale based on the manufacturer's experience or practice. For example, if thin walled cylindrical parts over a certain L/D range frequently present distortion or out-of-round problems because of the process or machine tools or fixtures, the process model would include intermediate machining steps to ensure a good part.

2.2.2 Family of Parts Classification

Generally speaking, a part design can be examined in the computer by automatic means and operation requirements for each surface determined based on the theoretical capabilities of various production methods and the initial raw material state. A more difficult problem, however, is sequencing the operations. The sequence is based on machine tool capacities, operation precedence, and process requirements. The latter includes requirements to machine locating surfaces. CPPP currently deals with the sequencing problem by developing process models for families of parts. A manufacturer is able to formulate process logic for part families more easily because there is only a finite number of design characteristics to consider and there is usually the process experience to draw on.

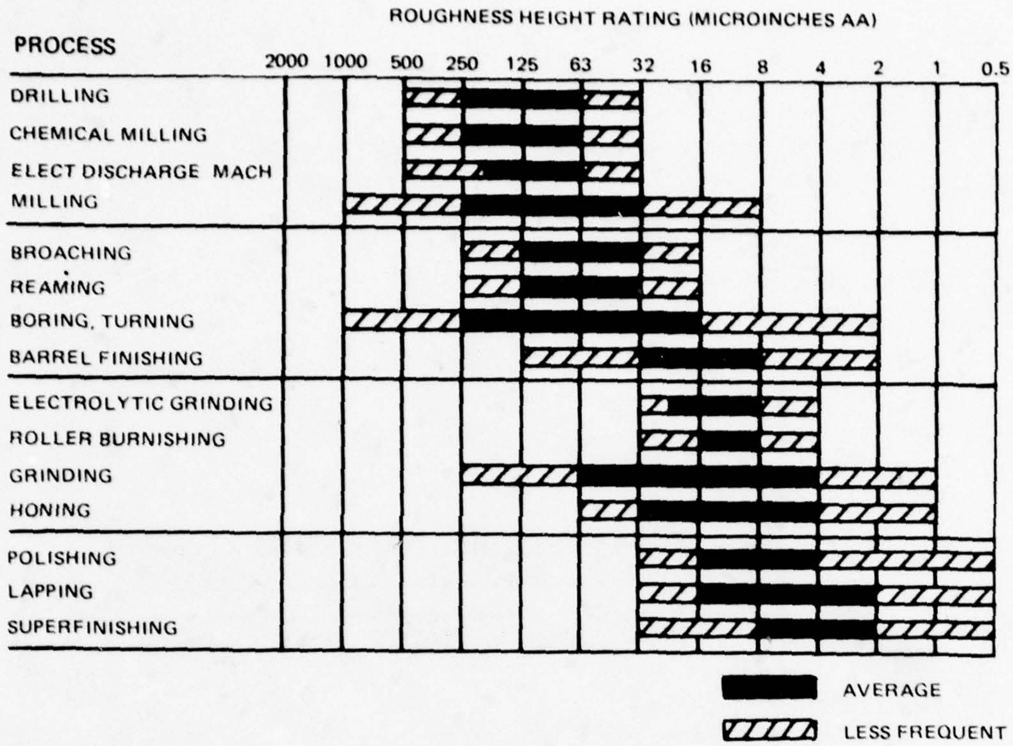


FIGURE 9. TYPICAL SURFACE FINISH RANGES FOR PRODUCTION PROCESSES (Data produced by General Motors in 1971)

CPPP allows the manufacturer complete freedom in defining part families. Figures 10 and 11 show four different part designs. They are all sleeve components used in fuel controls. The part geometries are quite different. The two parts of Figure 10 are made from nitralloy bar stock and require special processes of nitriding, copper and nickel plating and electrofilming. The parts of Figure 11 are made of AMS 5616 steel. The sleeves normally do not exceed 6 in. long or 2 in. in diameter. They have tight tolerances and finish. They may have thru bores. Each of these parts require a nitriding process different from the parts of Figure 10 and different from each other. In one case, Type B nitride is required and in the other Type A nitride. The processes involved are quite different.

The grouping of sleeves into part families for purposes of defining process models can occur in several ways. The sleeves of all four types could be classified as one family. In that case, it would be necessary to "code" all parts as "sleeves" and one process model would be defined for all possible geometry, material and process variations. This would be a fairly complex model. Another approach would group nitralloy sleeves and AMS 5616 sleeves of type A and B nitride into their own respective part families. This would classify parts primarily by process -- the process models would then be required to accommodate shape and geometry variations.

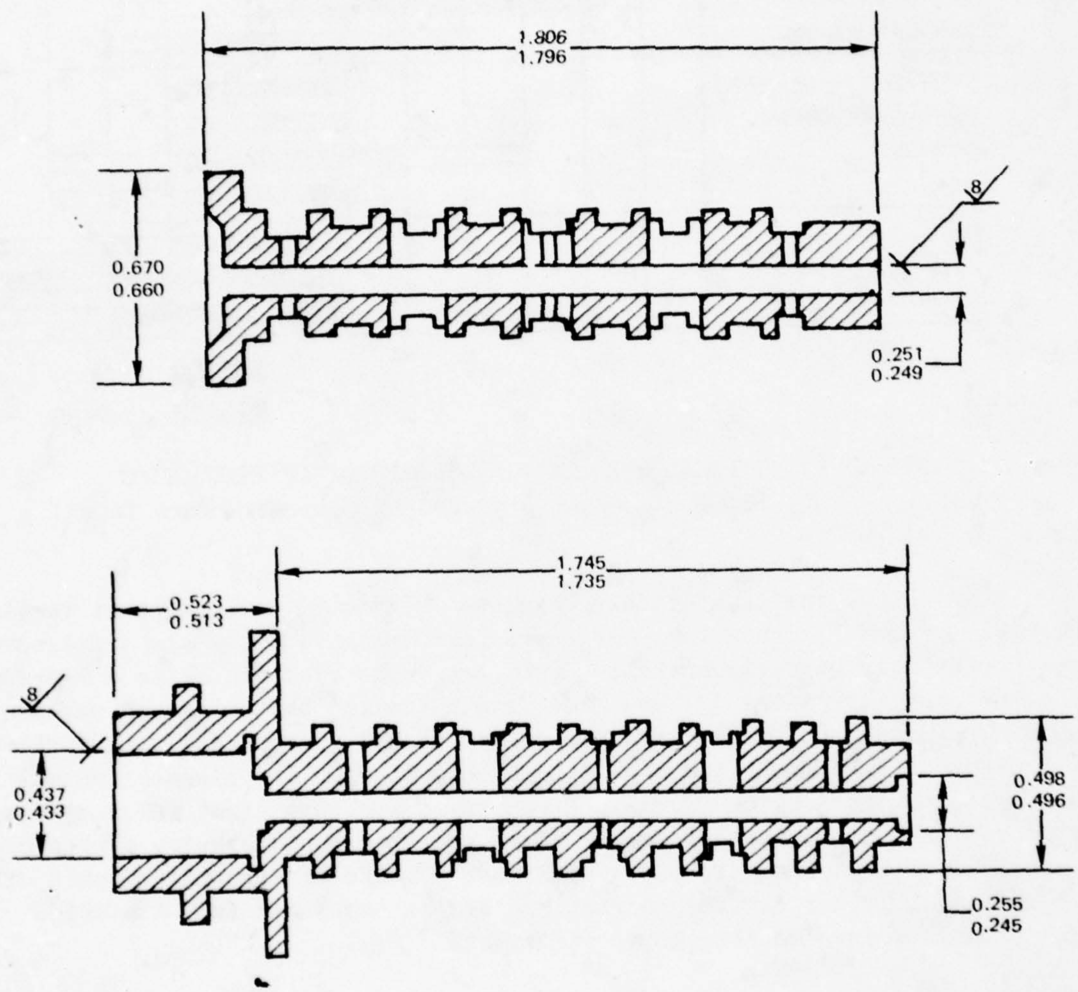
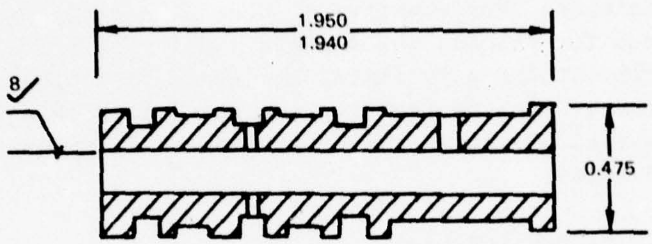
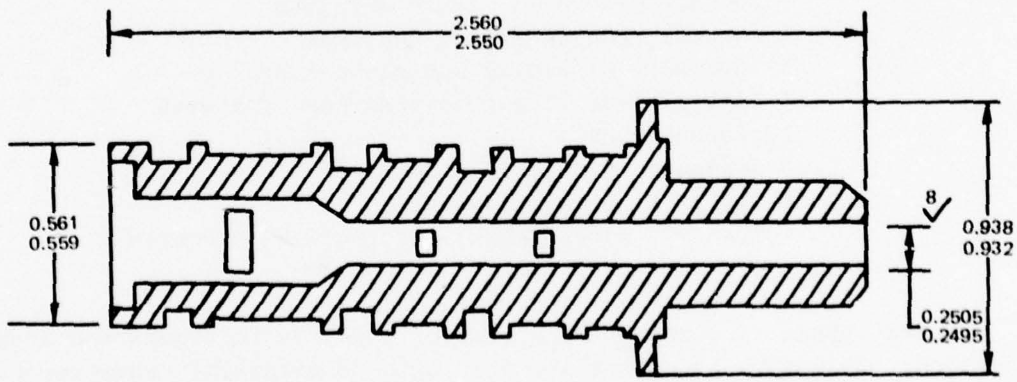


FIGURE 10. EXAMPLES OF NITRALLOY SLEEVES



AMS 5616, TYPE B NITRIDE (BORE)



AMS 5616, TYPE A NITRIDE (ALL OVER)

FIGURE 11. EXAMPLES OF SLEEVES REQUIRING DIFFERENT PROCESSES

2.2.3 Formulation of Process Models

The process model for a part family defines the rationale for determining a sequence of operations and specifying particular part surfaces affected by each operation. To develop a model, the manufacturer would first formulate a general process for the specified part family. The general process is simply an outline of the steps that may be required to fabricate a particular part of the family. Process steps must be included for any variation allowed by the part family definition. For example, if deep hole drilling is required for some parts and not for others, the process model must provide for the possibility. Similarly, if the part family has large variations in surface and finish requirements, types of features, or special process requirements, the process model must allow for them. An outline of the general process for sleeves is shown below.

- draw material
- shape bar stock
- install deep hole
- complete shaping
- hone and/or grind for form conditions
- finish turn
- install grooves by crush grinding
- install noncylindrical features
- harden by nitriding and plate surfaces
- install remaining noncylindrical features
- finish machine
- harden by type A nitride
- finish to prenitride size
- inspect, clean, mark, electrofilm, preserve and pack part

The next phase of formulating a process model is to expand the steps of the general outline by incorporating the logic to determine requirements for specific types of operations. The logic would be developed based on geometry, dimension, finish, material and special process variations allowed in the part family definition. In the above outline, for example, the requirement for deep hole drilling is dependent on the size and length of the thru bore (if one exists). Initial shaping of the part may result in drilling the bore if the size does not require a deep hole operation. Small stepped diameters that can be finish ground in one operation would not be rough turned when shaping the part. Only certain groove features would be turned, others would be crush ground. Diameters are also machined during crush grinding under certain circumstances. Parts made of certain materials may require heat treatment early in the process followed shortly thereafter by a stress relief. Logic would also be included to generate a finish turn operation for part surfaces that can not be finished during shaping operations and do not have tolerance conditions that require grinding.

Logic would be included to machine noncylindrical features (slots, flats, windows) and drill holes if they are specified in the part design. The sequence for installing these features would depend on "timing feature" requirements and the type of feature. Certain features that break into the bore or are of a certain shape may not be installed until later in the process. The general outline above shows that these features are installed following any requirement for nitriding.

The logic for hardening the part by a nitride process and plating surfaces could depend on several variables. Part material and the type of nitride process specified are key parameters upon which the sequence of operations depends. Only under certain conditions is the entire part nitrided. In situations where specific surfaces are to be nitrided, the process model must provide for masking. The masking process is dependent on the type of part material. Requirements for final plating (e.g., nickel) would follow the nitride process and the removal of the protecting mask material.

Requirements for finish machining (hone, grind, lap) are dependent on tolerance, surface finish and form conditions and whether nitriding is required. The final operations to be covered by the logic are requirements for inspection, cleaning, marking, preserving and packing. The requirement for electrofilming would also be determined in this part of the model.

The end result of incorporating logic into the general process outline for a part family is a process model. The model will generate different sequences of operations conditional on variance in design data. Figure 12 shows an example of an operation sequencing structure that might be found in a process model. Each element or box is the equivalent of a sequence "branching" logic or a test for generating an operation. Boxes from which either of two "paths" can be followed are branching elements of the model. The path followed depends on whether the specific condition is true or false for the part being planned.

For example, boxes 38, 39 and 40 might be elements of the process model to install noncylindrical features and stress relief the part if the material is AMS 5616 and type A nitriding is required. Box 38 would perform a test to determine if the part material is AMS 5616. If the answer is true, the process model would branch to box 39 where another test would be made to determine if the part has a requirement for type A nitride. Again, if the answer is true, the process model would branch to box 40. At this element a test might be made to determine if the part has a timing feature requirement that should be installed before machining the noncylindrical features. If at any of these branch points the answers were false, a different path would be followed. A false answer at element 38, for example, would result in a transfer to box 45. This element would be a test for generating a metalcutting or non-metalcutting

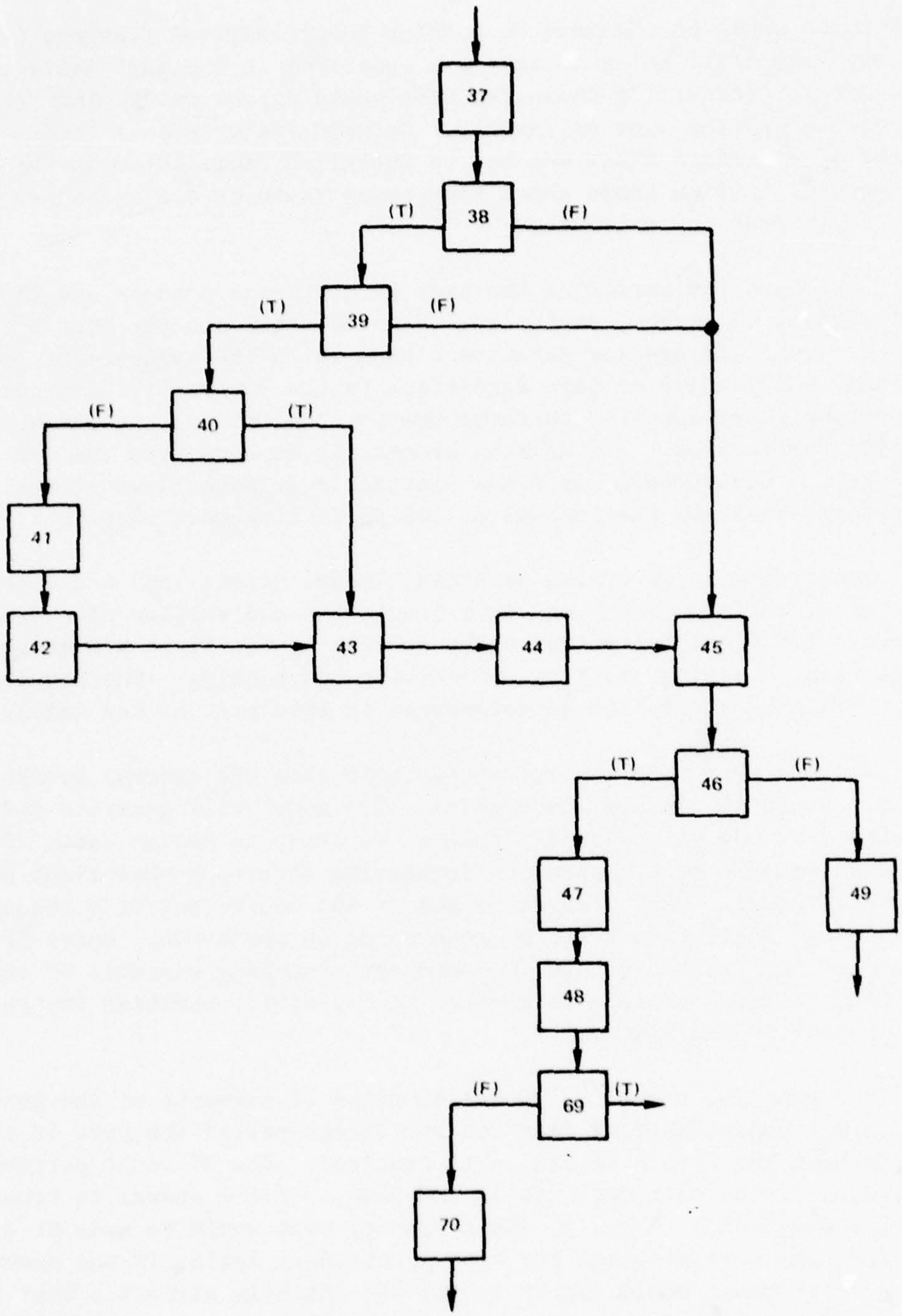


FIGURE 12. EXAMPLE OF OPERATION SEQUENCING STRUCTURE IN A PROCESS MODEL. Boxes are either branch points or tests for operation requirements.

operation, such as an OD grind on a centerless grinder or copper plating surfaces. Whether an operation would be generated would depend on the design characteristics of the part being planned.

It can be seen in the example of the operation sequencing structure that there are twelve possible paths. Two of the paths are:

(1) 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 69, 70

(2) 37, 38, 45, 46, 49

This means there are at least twelve sequences of operations that could be generated. There are in fact many more. For example, boxes 37 and 45 are tests for generating operations. Depending on the part design, an operation may or may not be generated in either case. Therefore, in path (2) above, four different operation sequences could be generated. Since both of these boxes occur in all twelve possible paths of the operation sequencing structure, there is a minimum of forty-eight (48) possible sequences of operations. Boxes 41, 42, 43, 44, 47, 48, 49 and 70 are also tests for generating operations. Thus, the number of possible operation sequences gets much larger.

The remainder of this section will illustrate the different program elements of a process model that are represented as boxes in the operation sequencing structure of Figure 12 . The elements of logic used to form a process model are:

- simple metalcutting axiom
- multiple operation metalcutting axiom
- single feature metalcutting axiom
- non-metalcutting axiom
- branching or program transfer axiom

2.2.3.1 Simple Metalcutting Axioms

Figure 13 is an example of a simple metalcutting axiom that would normally be placed at the beginning of a process model. The rationale in this axiom is to machine any outside surface of the part on an automatic bar machine conditonal on a surface being an open diameter, an exposed semiopen diameter, or an end. This axiom would cause CPPP to generate a turn, face, and cut-off operation to shape a piece of bar stock and cut it off. The type of data generated is shown in Figure 7, operation 0010.

Axiom vocabulary and structure are important in formulating the rationale. The vocabulary includes key words. For example, the term "outside surface" will cause CPPP to only test surfaces on the external periphery of the part;

Turn outside surface on MC0400 (Automatic Bar) in normal if Surface is an open diameter (or) Surface is a semiopen diameter, surface is exposed (or) Surface is an end $

FIGURE 13. EXAMPLE OF AXIOM TO SHAPE BAR STOCK
Logical expression: $A + (B \cdot C) + D$

internal surfaces are not considered by this axiom. The term "normal" means that the part design should be oriented in the direction of normal. Orientation axioms are used to define the normal orientation of a part; one of the first axioms of a process model would orient the part for subsequent CPPP analysis. Terms like "open diameter", "semiopen diameter", "exposed", and "end" are vocabulary used by the manufacturer in formulating the process model. Their meaning must be defined to CPPP. Appendix F defines vocabulary terms used in the demonstration process model for a part family of nitralloy sleeves.

The structure of an axiom is equivalent to a Boolean (logical) expression. The expression must be true for at least one part surface before an operation can be generated. All surfaces for which the Boolean expression is true will be cut in the operation. If the Boolean expression is false for all part surfaces, an operation will not be generated and CPPP will go on to the next axiom in the operation sequence structure.

The above axiom results in a simple Boolean expression:

$$A + (B \cdot C) + D = (1,0)$$

where

A = 'open diameter'
B = 'semiopen diameter'
C = 'exposed'
D = 'end'

Figure 14. illustrates the "syntax tree" which shows how CPPP evaluates the Boolean expression for each outside part surface. Given a particular part surface, the evaluation begins by testing for an open diameter. If the answer

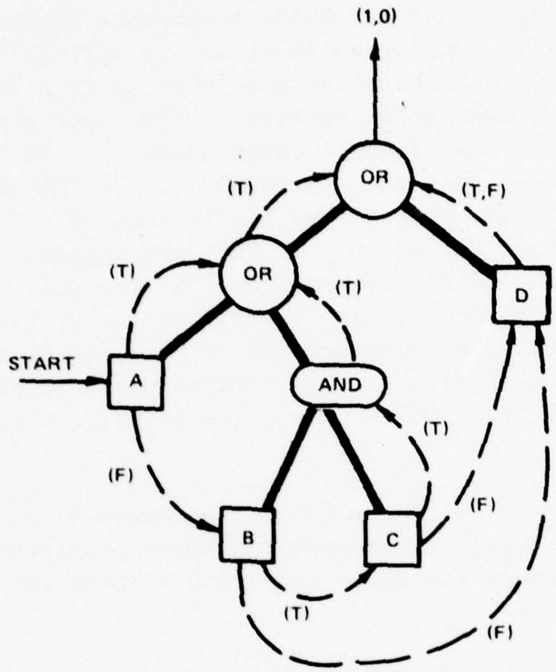


FIGURE 14. EXAMPLE OF SYNTAX TREE FOR LOGICAL EXPRESSION: A + (B·C) + D. T = true; F = false

is true, then by following the truth path (T) it can be seen the expression is true. This would cause CPPP to generate a turning operation for the particular surface. CPPP would then continue to the next part surface and repeat the evaluation procedure. Conversely, if the answer were false to the initial test, CPPP would follow the false path (F). This leads to the next test which is to determine if the surface is a semiopen diameter. If the answer is true, the syntax tree shows that a further test is needed to determine if the surface is exposed. Further evaluations of the Boolean expression by the syntax tree can be verified by the reader.

Every process axiom has a syntax tree. The coded form of an axiom, which is generated by the CPPP Language Processor, is equivalent to the logic portrayed by its syntax tree.

Figure 15 is another example of a simple metalcutting axiom. The purpose of this axiom in the model from which it was taken is to finish shaping the part in reverse orientation on an automatic chucker or NC lathe. (The model had previously provided for shaping surfaces of the part in the normal orientation on a bar machine.) The operation generated by this axiom could result in machining both outside and inside surfaces. The upper portion of the axiom specifies the rationale for machining outside surfaces. It provides for cutting open diameters that were not previously cut on the bar machine, semiopen diameters, the free end, reliefs and the largest OD. It also states that open and semiopen diameters be cut only if they are exposed. The largest OD will be finish turned only if its tolerance is between .004 and .010 and any specified concentricity requirement is looser than .002. This rationale implies that surfaces with a more open tolerance can be finished by the initial bar machine operation. Also, a surface with diametral tolerances tighter than .004 or concentricity tighter than .002 will require grinding and, therefore, should not be turned again.

Table 1 shows the full rationale of the manufacturer with respect to largest OD for the part family of sleeves. Similar conditions govern the machining of other diameters and faces that form stepped shoulders (semiopen

TABLE 1. MODEL RATIONALE FOR LARGEST OD

Surface Condition	Machine Requirement	Operation
solid	bar machine	turn
$.004 \leq t < .010$ $\odot > .002$	automatic chucker NC lathe	finish turn
$t < .004$	OD grinder centerless grinder	grind
$\odot < .002$	OD grinder centerless grinder	grind

t = tolerance
$\odot$ = concentricity

```
Turn outside surface on MC2400 (automatic chucker) or MC2500 (NC lathe)
in reverse if

            Surface is an open diameter,
                surface is not cut,
                surface is exposed (or)

            Surface is a semiopen diameter,
                surface is exposed (or)

            Surface is a free end (or)

            Feature is a relief,
                feature location is .LE 0.5* part length (or)

            Surface is largest OD
                diametral tolerance is .LT .010,
                diametral tolerance is .GE .004,
                concentricity is .GE .002 $

        (c) Turn inside surface if

            Feature is a thru bore,
                feature is not cut (or)

            Feature is a counterbore,
                feature is exposed,
                feature is not a sharp edge feature (or)

            Feature is a groove,
                feature is a counterbore feature,
                feature is exposed $
```

FIGURE 15. EXAMPLE OF SIMPLE METALCUTTING AXIOM
Logical expression (top): $(A \cdot \bar{B} \cdot C)+(D \cdot C)+E+(F \cdot G)+(H \cdot I \cdot J \cdot K)$
Logical expression (bottom): $(L \cdot \bar{B})+(M \cdot C \cdot \bar{N})+(O \cdot P \cdot C)$

diameters) and counterbores. These surfaces, however, may have other conditions for operations that are related to special process requirements of hardening and plating. Also, surface finish and form conditions of straightness, roundness, etc., generate requirements for operations.

The lower portion of the axiom in Figure 15 specifies the rationale for machining inside surfaces. It provides for cutting the thru bore, counterbores, and grooves located in a counterbore. The thru bore will be cut only on the condition that it was not previously cut in an earlier operation. If the bore is a deep hole, the model will cut it with an ejector or gun drill following the initial bar machine operation. An exposed counterbore will be cut in this operation providing it is not a "sharp edge feature". These features are installed by grinding following any requirement for nitriding.

Figure 16 shows another example of a simple metalcutting axiom programmed to crush grind grooves and outside diameters that have not been cut or have tolerances less than .004. This axiom also requires that the separation between grooves to be crush ground be greater than .060. This requirement is based only on the process of crush grinding.

```
Crush grind outside surface (grooves) on MC1400 (crush
grinder) in normal if

     feature is a groove,
         feature is not cut (or)

     feature is a semiopen diameter,
         feature is not cut (or)

     feature is a semiopen diameter,
         diametral tolerance is .LT .004

providing the following condition exits:

     groove separation (0.060) $
```

FIGURE 16. EXAMPLE OF SIMPLE METALCUTTING AXIOM
Logical expression: $(A \cdot \bar{B})+(C \cdot \bar{B})+(C \cdot D)$

Figure 17 shows an example of a simple metalcutting axiom programmed to generate finishing operation on the thru bore. It requires the thru bore to be lapped with a hand hone whenever the surface finish or tolerance is no greater than 8 or .0004 respectively or when the straightness or roundness form condition is no greater than .0001.

Lap the thru bore on MC1700 (hand hone) in normal if

Surface finish is .LE 8 (or)

Diametral tolerance is .LE .0004 (or)

Straightness is .LE .0001 (or)

Roundness is .LE .0001 $

FIGURE 17. EXAMPLE OF SINGLE FEATURE METALCUTTING AXIOM
Logical expression: A+B+C+D

2.2.3.2 Multiple Operation Metalcutting Axiom

This class of metalcutting axioms is similar in form to the simple metalcutting axioms. The only difference is that multiple operation metalcutting axioms instruct CPPP to generate one operation for each part surface for which the axiom's rationale is true.

Figure 18 shows an example of a multiple operation metalcutting axiom. It can be identified by the key word "each" in the statement of the operation. This axiom will cause a grind operation to be generated for each inside diameter that is exposed and whose tolerance is less than .002. The rationale also states that this axiom does not apply to the thru bore.

Grind each inside surface on MC1600 (ID grinder) in normal if

Surface is a diameter,
surface is not a thru bore,
surface is exposed,
diametral tolerance is .LT .002 $

FIGURE 18. EXAMPLE OF MULTIPLE OPERATION METALCUTTING AXIOM
Logical Expression: $A \cdot \bar{B} \cdot C \cdot D$

Figure 19 is another example of a multiple operation metalcutting axiom programmed to generate a milling operation for each "window" that is exposed and was not previously cut. A window is a term for an opening into the bore. A further condition of the rationale is that the edge where the window breaks into the bore have a radii of greater than .005. (Windows with smaller radii will be installed by an EDM process following any requirement for nitriding.) The rationale also requires that the "timing feature" be machined before installing a window. If a window has no associated timing feature, then the condition does not apply. In the case where multiple patterns of windows must be installed, an operation is generated for each pattern. A pattern of windows or any other noncylindrical feature is when more than one feature exists in a cross-section of the part.

```
Mill each outside surface (window) on MC1300 (miller)
in reverse if

      Feature is a window,
          feature is not cut,
          feature is exposed,
          bore edge break is .GT .005

providing the following condition exists:

   timing condition met $
```

FIGURE 19. EXAMPLE OF MULTIPLE OPERATION METALCUTTING AXIOM FOR NONCYLINDRICAL FEATURE

Logical Expression: $A \cdot \overline{B} \cdot C \cdot D$

2.2.3.3 Single Feature Metalcutting Axiom

A single feature metalcutting axiom is programmed to generate an operation on one part surface. Figure 20 shows an example of a single feature metalcutting axiom. The axiom is programmed to hone the thru bore on an automatic hone. An operation will always be generated whenever this axiom is encountered in the process model. The only condition is that the part have a thru bore.

```
Hone the thru bore on MC0900 (automatic hone)
in normal $
```

FIGURE 20. EXAMPLE OF A SINGLE FEATURE METALCUTTING AXIOM

2.2.3.4 Nonmetalcutting Axiom

Nonmetalcutting axioms have the same form as metalcutting axioms and result in the generation of operations. The only difference is that CPPP knows that these operations do not result in the removal of metal. They generally cover requirements for special processes, inspection, etc. Figures 21 and 22 show examples of nonmetalcutting axioms respectively programmed to generate nitriding and inspection operations. The nitriding axiom specifies that the process is to use furnace 2780 and that the manufacturer's process standards HS1173 and PMP505 apply. This axiom assumes a particular nitriding steel. For a different material, the process standard may vary; either a more general axiom is required to accommodate multiple materials or a different axiom is needed for each type of material affecting the process standards. Each surface to be nitrided by this operation will be identified by CPPP.

```
Nitride in MC0200 (Furnace), MT0203 (Furnace 2780)
per HS1173 and PMP505 if

    Surface is a nitrided surface $
```

FIGURE 21. EXAMPLE OF NONMETALCUTTING AXIOM TO GENERATE NITRIDE OPERATION.
Logical Expression: A

```
Sample roundness of the thru bore with MC1900
(proficorder) $
```

FIGURE 22. EXAMPLE OF NONMETALCUTTING AXIOM TO INSPECT THE THRU BORE.

2.2.3.5 Branching Axiom

In the earlier discussion about formulating process models, the concept of operation sequencing structure was introduced. This structure consists of the different kinds of metalcutting and nonmetalcutting axioms and the logic for generating different sequences of operations. A principal element used in formulating the operation sequencing structure is the branching axiom. This axiom allows the manufacturer to construct process models for a large variation of material, geometry and process conditions. The axiom will cause CPPP to test for specific part design characteristics and transfer (or branch) to the appropriate section of the process model. Figure 12 illustrates the effect of branching in a process model. Figure 23 shows several examples of branching axioms. The first one is programmed to transfer to element 0150 of the process model if the part has a timing feature requirement. Otherwise, CPPP will transfer to element 0240. Branching axioms can be specified to test for any condition. The next two examples show branching axioms that test for surface finish requirements less than 16 and part material of AMS 5630 respectively.

```
Do 0150 if part has timing feature requirement, else 0240 $

Do 0200 if surface finish requirement is .LT 16, else 0320 $

Do 0110 if material is .EQ AMS 5630, else 0150 $
```

FIGURE 23. EXAMPLES OF BRANCHING AXIOMS

2.2.4 Use of Process Models

As stated earlier in this section, process models provide the necessary rationale for CPPP to plan a sequence of operations. The models consisting of metalcutting and nonmetalcutting axioms and branching axioms are converted into a computer code and stored in the data base. A complete model for the demonstration nitralloy sleeve family is given in Appendix E. CPPP will plan the sequence of operations for a nitralloy sleeve by using the process model and a full description of the part design. The process planner can also interact with the system to make any desired modifications. All data generated about operations is stored by CPPP in the data base so that it is available to plan operation details and calculate workpiece dimensions and tolerances. The latter function will determine if the process is good from the standpoint of producing acceptable parts.

2.3 Plan Operation Details

The CPPP operation detailing function provides detailed information for each operation in the sequence of operations. The task of the detailing module is to determine the best machine tool (if a particular one is not specified), best cut sequence, best cutting tools, and best machining parameters to use for each operation. In initiating CPPP, the process planner must indicate whether he wishes these choices made to minimize machining time or machining cost. As illustrated in Figure 24, this task is one of finding the best path through a network of possible choices. The figure shows two machine tools that could be used for the operation. Each machine tool has three possible cut sequences, with two cut sequences being possible on both machines. The four cut sequences have respectively three, four, four, and three possible tool combinations, two of which are unique to one sequence and the other six of which are shared by two sequences.

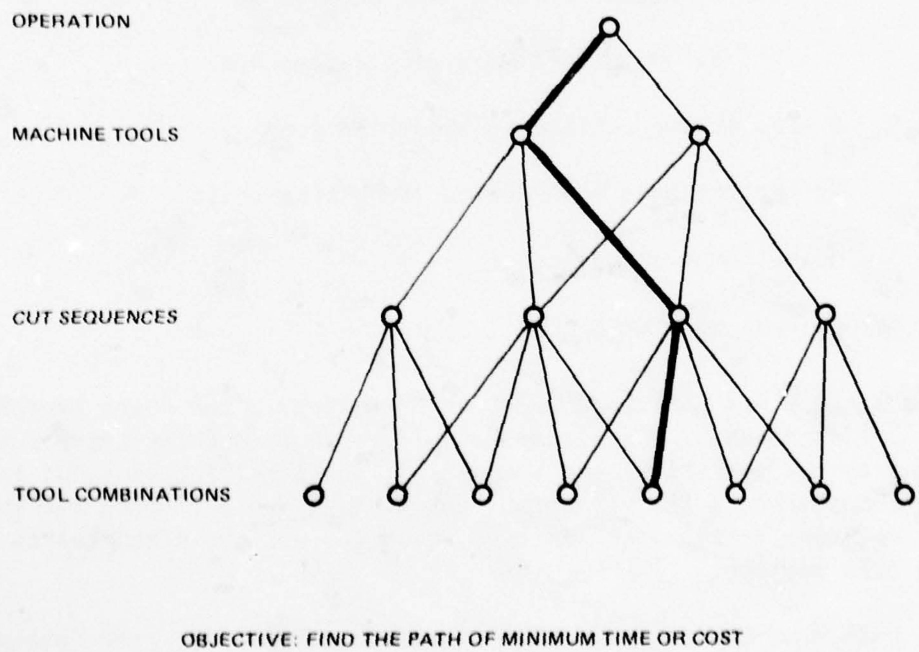


FIGURE 24. THE DETAILED PLANNING NETWORK PROBLEM

The cost (or time) of the operation on a machine tool is that of the best cut sequence on that machine tool. The cost of a sequence is in turn that of the best combination of cutting tools operating at chosen feeds, speeds, and cut depths. The heavy line in the figure represents the best choice. To identify the best path in the network, all paths must be generated, examined, and evaluated.

The nine functions that must be performed to arrive at the best path through the network are given in the following list. Successive levels of indentation indicate successive levels of functional nesting. For example, level two is repeated several times to solve level one and each repetition of level two requires several repetitions of level three.

1. Determine machine tool candidates
    2. Determine cut sequence candidate
        3. Determine types of cuts
            4. Determine cutting tool candidates
                5. Calculate Machining Parameters
        6. Formulate cutting tool combinations
        7. Select best combination of cutting tools
    8. Select best cut sequence
9. Select best machine tool

Functions 1 and 9 are performed once per operation; 2 and 8 are performed each machine tool candidate. Functions 3, 6, 7 are performed for every cut sequence considered in the operation, and 4 and 5 are performed for each cut in every sequence considered in the operation, and 4 and 5 are performed for each cut in every sequence. Each of these nine functions will be discussed in depth later in this section.

The main emphasis in generating operation details has been development of the analytic framework necessary to do the job. The current mode of operation relies heavily on interaction by the process planner to steer CPPP away from consideration of bad or uninteresting possibilities. The detailing modules are not yet fully developed and do not operate from stored process logic as the initial operation sequencing modules do. As a result, CPPP must generate and examine several different logical possibilities at

each detailing step and must attempt by time and cost estimates to make good selections. The estimates rely heavily on machinability analysis and values from the CPPP data base. The present system requires a manufacturer to estimate many data base values used in the analysis. Ultimately, these estimates should be replaced by more accurate methods of calculating the data values. Thus CPPP might expend considerable effort making estimates from poor data and make a poor choice if unaided by interaction by the process planner.

A solid framework has, however, been developed for CPPP operation detailing. This framework is dependent on having a description of each metalcutting and nonmetalcutting operation that has been included in the sequence. For metalcutting operations the description consists of the type of operation, type of machine tool (lathe, grinder, hone, etc.), the surfaces that are to be cut and the workpiece geometry. For nonmetalcutting operations such as heat treating, plating, coating, or inspection, it consists only of the operation type and machine type (furnace, bench, etc.). In addition to this information about the sequence to be planned, the detailing cycle requires complete information about the workshop. This data must include information about available machine tools, tooling resources, stock removals and tolerances for different cutting situations, and machinability. All of this workshop-dependent information must be stored in the CPPP data base, whence it is retrieved for operation detailing. The information about the specific operations is generated by the methods described in Section 2.2. The data is passed along in the form of an "operations matrix," a summary list of the operation descriptions, and the geometry of the raw material and finished workpiece.

Figure 25 shows a sample part. The first six operations on such a part, as found in the summary list of operation descriptions, might be as follows:

Op 10 - Draw barstock from raw material stores

Op 20 - Turn to rough shape and cutoff

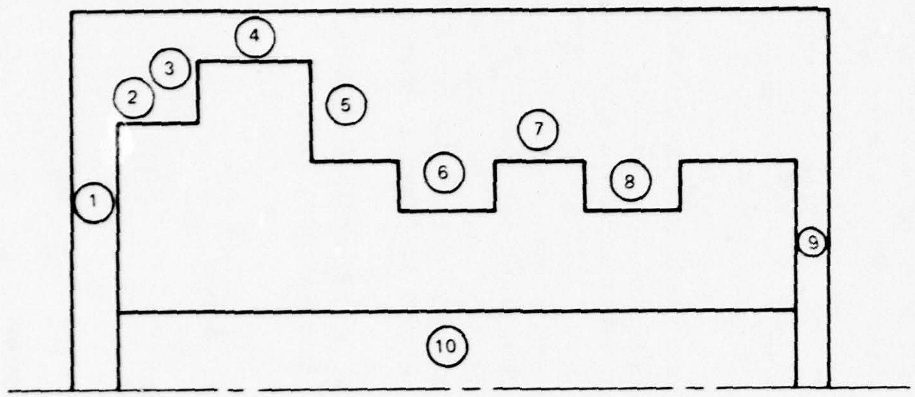
Op 30 - Heat treat to stress relieve

Op 40 - Centerless grind locating diameter

Op 50 - Gun drill through bore

Op 60 - Rough turn the cutoff end

This partial sequence of operations will be used to discuss the operation matrix, also shown in Figure 25.



	OPERATION DATA					AFFECTED SURFACES									
OP.NO.	MCT	SETUP	MC1	MC2	MT	E001	D002	F003	D004	F005	D006	G007	G008	E009	I010
10	–1	N	100	0	108	0	0	0	0	0	0	0	0	0	0
20	1	N	400	0	0	1	0	0	1	1	1	0	0	1	0
30	–1	N	300	0	301	0	0	0	0	0	0	0	0	0	0
40	5	N	500	0	0	0	0	0	0	1	1	0	0	0	0
50	2	R	600	0	0	0	0	0	0	0	0	0	0	0	1
60	1	R	2400	2500	0	1	1	1	1	0	0	0	0	0	0

FIGURE 25. FIRST SIX ROWS OF THE OPERATIONS MATRIX FOR A SAMPLE PART

At the top of the figure, the final part geometry is shown superimposed on a section of barstock. The part illustrated has an open outside diameter, two stepped outside diameters, two grooves, a through bore, and two ends. These surfaces are numbered in a clockwise fashion starting with the left end. By adding "E" for end, "D" for diameter, "F" for face, "G" for groove, and "I" for internal diameter to these surface numbers, the four-character CPPP surface names are formed (E001, D002, F003, etc.). The labels appear in the operations matrix.

At the bottom of the figure is the beginning segment of the operations matrix for this part. There is a matrix row for each operation, and the illustration shows the initial six operations described above. The operations matrix consists of two parts. The first five columns are for general operation data. The remaining columns, one for each part surface, tell which surfaces are cut or affected by the operation. The first column, MCT, identifies the type of machine class to be used. CPPP recognizes a hierarchy of three levels of machine classification. At the bottom is the identity of specific machine tools such as B&S No. 2 Automatic Bar Machine or Micromatic 723 Automatic Hone. The middle level groups machine tools into classes such as automatic bar machines and automatic hones. The top level groups machine classes by types such as lathe and hone. MCT is a code representing this top level. The MCT Code -1 is used for noncutting equipment such as benches, tanks, and furnaces; 1 is the code for all types of lathes; 2 is for deep hole drills; 5 is for cylindrical grinders; and so on. The SETUP column determines whether the part is in Normal orientation as shown in the picture or in Reverse orientation for the operation. The MC1 and MC2 columns give the internal code numbers of the primary and, if specified, alternate machine class for the operation. For example, 400 is the code for bar machines, and 2400 and 2500 are the codes for automatic and NC chuckers. The MT column may specify a particular machine tool for the operation. In the figure a raw material bench (MT = 108) is specified for Operation 10 and a stress relief furnace (MT = 301) for Operation 30. The remaining columns (affected surfaces) have a 1 to indicate a surface is cut in an operation or a 0 to indicate it is not. A 1 is also used to indicate that a surface is affected by a special process, such as nitriding or nickel plating.

2.3.1 Determine Machine Tool Candidates

To determine the qualified machine tool candidates for an operation, CPPP first examines the MC1, MC2, and MT columns of the cut matrix. An entry in MT will cause the specified machine tool to be the only candidate and it is automatically qualified. Otherwise, all machine tools listed in the data base under the machine class identified in MC1 become possible candidates. If MC2 specifies an alternate class, all its machine tools are also included.

The possible list of candidate machine tools is then examined, one machine at a time, and those which qualify for the operation become part of the final list of qualified machines. Machines from the original list qualify for an operation if they can physically accommodate the workpiece and can perform the required cuts. The present version of CPPP disqualifies a machine tool only if the overall part length or diameter is too large or small or if some special feature -- such as bore diameter for a gun drilling operation -- is out of range. However, information is now available in the CPPP machine tool file and part design data to support more detailed analysis in the selection of qualified machine tools. For example, machines with horsepower ratings below a certain value could be eliminated for certain hard to machine materials. The types of cuts and their tolerance and finish requirements could also be used to restrict the number of machines considered. It is of practical importance to limit this number because a machining analysis is performed for each machine and can result in appreciable computer costs.

After qualification is finished the operation will be fully detailed on every qualified machine tool to determine which is the best one.

2.3.2 Determine Cut Sequence Candidates

The first step in identifying cut sequences is for CPPP to determine the aggregate material to be removed in the operation. Figure 26 shows the stock removal for Operation 20 of the cut matrix in Figure 24. From this figure it is easily seen that while there are five cut surfaces -- E001, D004, F005, D006, and E009 -- there will be only four cuts because D006 and F005 must be formed together from solid condition. CPPP recognizes these four cuts and orders them into different cutting sequences. Logically there are 24 possible sequences of the four cuts, but some of these are physically impossible and others may not be good machining practice. For example, the eighteen logical possibilities that place E001 first, second, or third in the sequence are physically impossible because barstock cutoff must be the last cut in the operation.

If the grooves were also formed in this operation, it would generally be preferable to cut them after D006 to avoid an interrupted cut on the diameter and to avoid cutting excess stock in a forming operation. It would also be logically possible to cut either groove first, thus doubling the number of possible cut sequences to be considered without adding anything of interest. For these reasons it is necessary for CPPP to apply some manufacturing intelligence to limit the number of candidate cut sequences. Bar machines in general require cutoff to be the last cut. Swiss automatics and tracer lathes require a single right to left cutting pass. On any manual machine it is important to cut the datum reference surface for the operation first. These are all examples of intelligence that are not yet implemented in CPPP, but which have been partially identified and can be further developed.

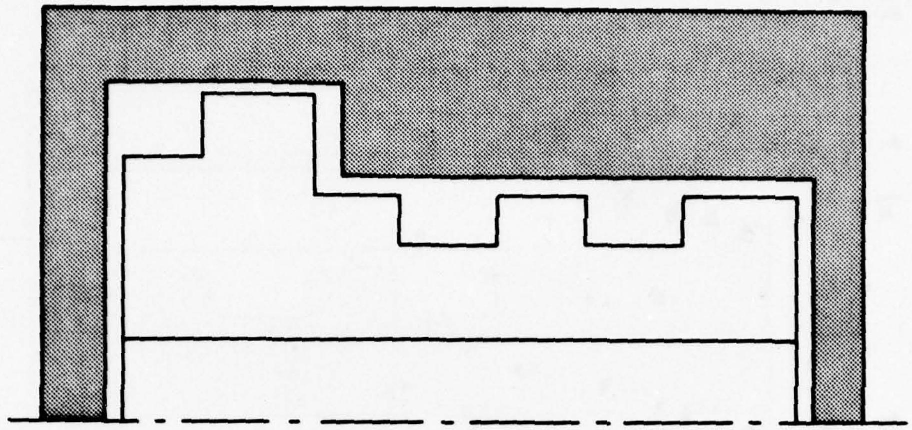


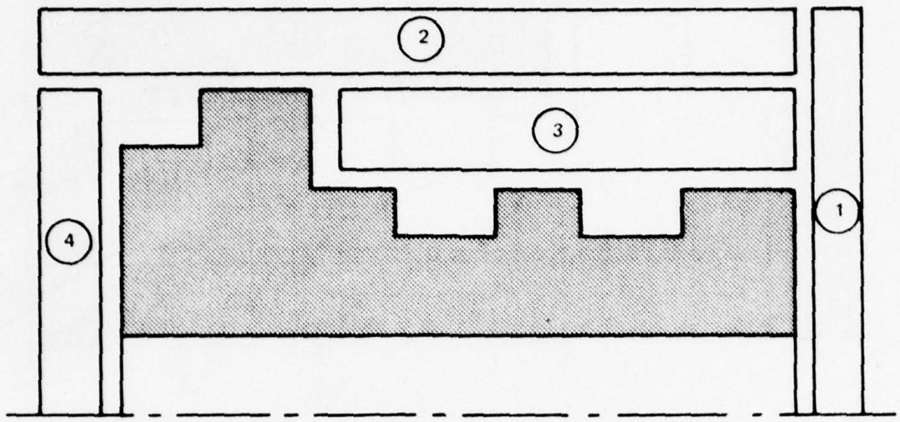
FIGURE 26. MATERIAL REMOVED IN AN OPERATION

What CPPP actually does is to follow heuristic rules to subdivide the total stock to be removed into regions. The regions themselves are ordered and are then each broken down into a subset of ordered cuts. The procedure used makes all rough cuts before any finish cuts, cuts diameters before forming grooves in them, etc. While these heuristics are being improved and eventually replaced by process decision logic, the process planner can use the CPPP interactive capability to modify or specify the cut sequence candidates.

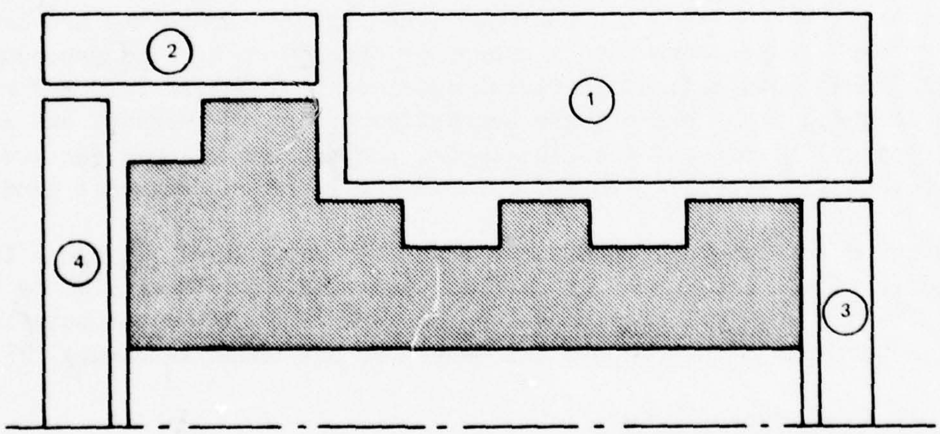
When the cut sequence candidates have been determined, each one is further detailed in turn. Any one of the cut sequences is an ordered list of the surfaces to be cut and implies a breakdown or decomposition of the material to be removed. Decompositions for two cut sequences are shown in Figure 27.

2.3.3 Determine Types of Cuts

The next problem for CPPP is to recognize the material decomposition for a cut sequence and to determine the type of cut represented by each element of the decomposition. To select appropriate cutter tools and to estimate cutting time and cost, CPPP must know the type of cut. Under the CPPP philosophy, each workshop is allowed to specify the types of cut each machine tool can make. For each cut type defined, a computer program is written and made part of the library of cut types known to CPPP. Figure 28 shows examples of some cuts included in the CPPP cut library; more are defined in Appendix G.



CUT SEQUENC E009, D004, D006, F005, E001



CUT SEQUENCE: D006, F005, E009, D004, E001

FIGURE 27. MATERIAL REMOVAL DECOMPOSITIONS

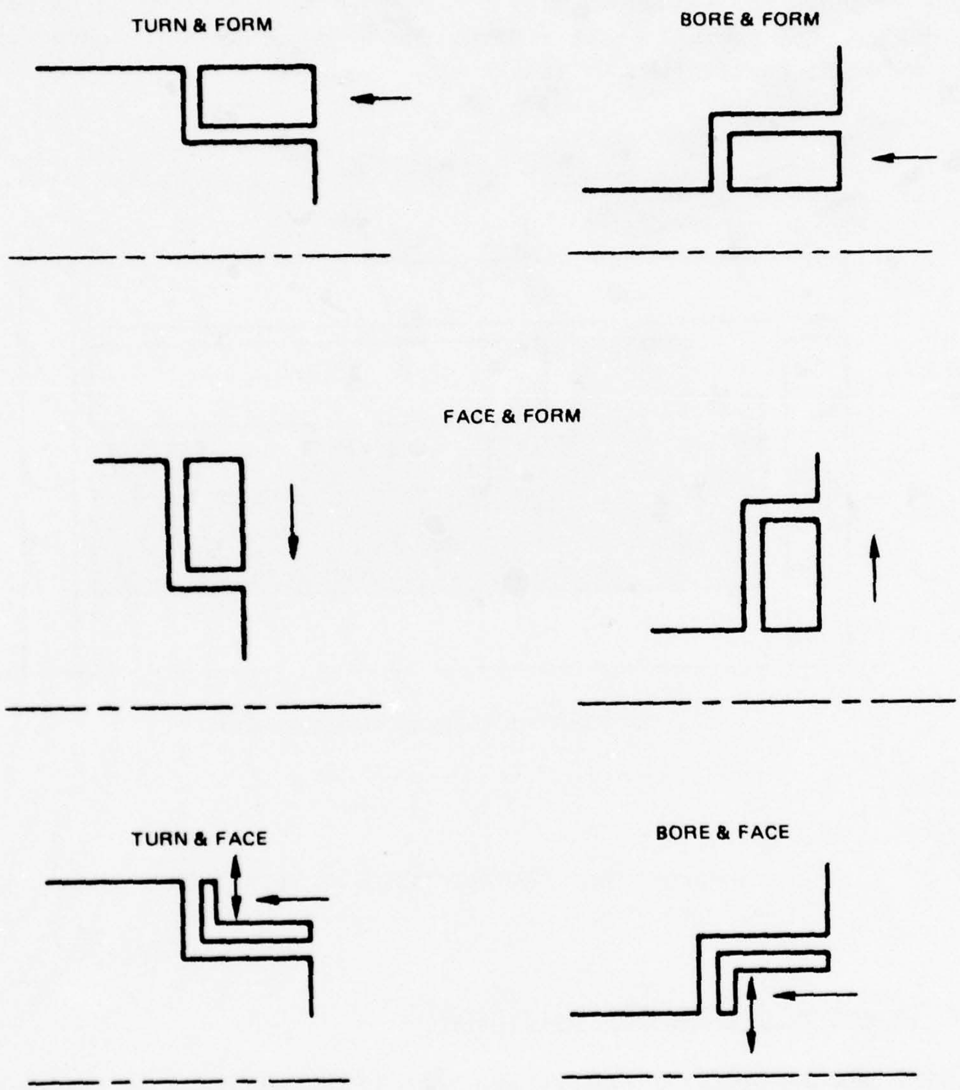


FIGURE 28. SAMPLE CUT APPLICATIONS

A list of all the cut types each machine tool can perform is stored in the CPPP data base. When a particular sequence of cuts is being considered for a particular machine tool, CPPP steps through the list of that machine's cut types. For each on it executes the corresponding library program on the first cut surface until one of them recognizes the first surface as its specific cut type. CPPP then advances to the second surface in the sequence, and so on. Figure 29 shows the result of this activity -- each cut has been identified by type. Also, the nominal stock removal can be determined for each cut and whether it is a rough, semifinish, or finish cut.

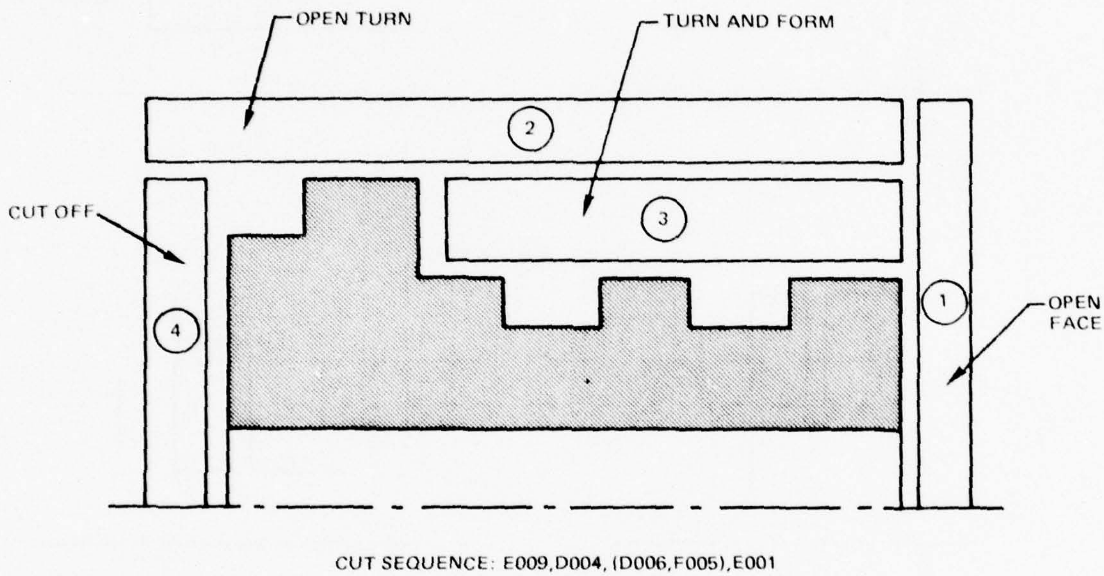


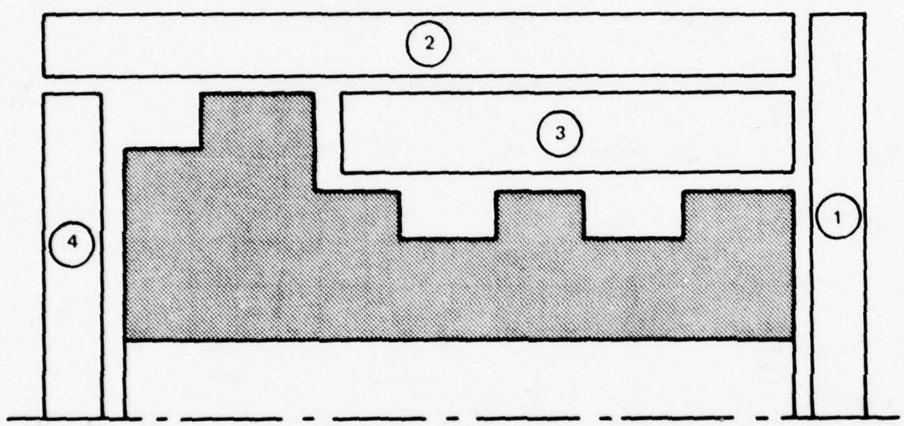
FIGURE 29. IDENTIFICATION OF CUT TYPES

2.3.4 Determine Cutting Tool Candidates

CPPP was designed to support two methods of cutting tool selection. Only one is currently implemented -- selection of types of tools based on the machine tool and the type of cut. Along with the list of cuts each machine tool can make, the CPPP data base includes one or more cutting tool candidates for each of the machine's cut types. (The cutter candidates are almost always tool types rather than specific tool numbers. Specific tools cannot be determined by cut type alone. It is necessary to know the actual cut parameters -- size,

fillet radius, part material, etc. -- that are encountered in particular cutting situations.) The second method is a capability for retrieving specific alternate tools using stored process logic from the data base. However, this capability is not being used by the present demonstration system. Either concept results in the situation illustrated in Figure 30, wherein each cut has a corresponding list of cutting tool candidates.

A more advanced concept not supported by the current design is to interface CPPP with a separate tool selection system that operates off of the workshop's tooling catalog. CPPP would pass cut description data to this system, which would provide specific tooling candidates.



CUT	SURFACES	CUT TYPE	CUTTING TOOLS		
1	E009	OPEN FACE	TOOL-1	TOOL-2	
2	D004	OPEN TURN	TOOL-1	TOOL-3	
3	D006,F005	TURN & FORM	TOOL-1	TOOL-3	TOOL-4
4	E001	CUTOFF	TOOL-5		

FIGURE 30. CUTTING TOOL CANDIDATES

2.3.5 Calculate Machining Parameters

Each cut is analyzed to determine its feed, speed, depth of cut, and number of cutting passes. These machining parameters are included as part of the detailed data on the operation sheets for metalcutting operations. They are also needed to calculate production times and costs. The CPPP framework

repeats this analysis of machining parameters not once per cut, but for every cutting tool candidate for each cut. Although CPPP does currently select only tool types and not actual cutters, this provision is made to allow the subsequent addition of actual cutter selection. When the actual cutter and its geometry are known, they become important parts of the overall cutting situation and can alter the machining parameter results. In particular, the shape and size of single point turning tools limit the maximum depth of cut per cutter pass.

Table 2 shows the list of machining parameters of importance to computerized process planning. The asterisks identify those parameters not determined by the present version of CPPP. In addition, since the present version normally uses only tool types, the machining parameters are the same for each cutting tool candidate for a specific cut.

TABLE 2. CPPP MACHINING PARAMETERS

1. Number of passes	9. Parts per tool
2. Depth of each pass	10. Chip Volume (per piece)
3. Feed	11. Rake Angle*
4. Speed	12. Nose radius*
5. Cutting rate	13. Tool material
6. Cutting time (per piece)	14. Tool cost per cutting edge*
7. Cut cost (per piece)	15. Force on tool tip*
8. Tool life	16. Horsepower required
	17. Spindle torque*

In manual process planning there is no standard method of determining feed, speed, depth, etc. Often this is left to the machinist. That cannot be done with CPPP because the system needs at least estimates of these values to make its selection of cutting tools, cut sequence, and machine tool. It is also CPPP philosophy to standardize the process as much as possible by having CPPP encompass all processing decisions, even if some must be sometimes overridden manually. If a process planner does specify machining parameters, the most systematic method in common usage is for him to refer to machinability handbooks. Handbooks are generally organized by type of cut (turning, drilling,

surface grinding, etc.), part material and hardness, and depth of cut. For each combination of these in the handbook, there will be a recommended feed, speed, and cutter material and often estimated tool life.

The handbook method is easy to use manually and easy to computerize because it involves a simple table look-up. However, the handbook does not offer the flexibility of varying the parameter recommendations. On some jobs it is best to remove metal as fast as possible even though more cutters are consumed; on others a high cutter cost or long cycle time may require longer tool life and a consequently slower cutting rate. Expressing machinability data as continuous functions of several variables -- such as extended Taylor tool life formulas or multiple regression equations -- greatly increases the flexibility of machining analysis and opens the door to optimizing machining parameters for particular cutting situations.

Currently, CPPP references its data base to determine the maximum depth of cut the machine tool can make on a single cutting pass. This is divided into the stock removal for the cut to determine the number of passes required. The stock removal is then divided up evenly across the cutting passes, and that value is the depth of cut that is used for look-up. CPPP looks up the machine class, type of cut, part material, hardness, and this depth of cut in the machinability file of its data base to read out recommended tool material, feed, speed, and estimated tool life.

Once the recommended machining parameters for a cut have been determined, they can be included in the detail operation information and used further by CPPP in the analysis of the operation details. In particular, machining parameters are used to help estimate time and cost data for individual cuts, combinations of tools, cut sequences and machine tools. These estimates are used by CPPP to select the tools, sequence, and machine for the operation.

The actual equations used by CPPP are the following:

$$t_c = N \bullet \frac{\pi \bullet d \bullet L}{f_r \bullet V} \bullet \left(1 + \frac{t_r}{T}\right) + t_t$$

$$c_c = (c_\ell + c_m) \bullet \frac{t_c}{60} + \left(N \bullet \frac{\pi \bullet d \bullet L}{f_r \bullet V} \bullet c_r\right)/T$$

t_c	=	cutting time (min)	c_c	=	cutting cost ($)
N	=	number of passes	T	=	tool life (min)
d	=	depth of pass (in.)	t_t	=	traverse time (min.)

L = cut length (in.)

f_r = feed (in./rev)

V = speed (in./min)

t_r = tool replacement time (min)

c_ℓ = cost of labor (\$/hr)

c_m = cost of machine (\$/hr)

c_r = cost of replaced tool (\$)

In the first equation t_t, traverse time between passes on the same cut, is currently set to zero. Ultimately it could be determined and included by standard time calculations. Derivation of other terms in the time equation has already been discussed. One of these, the depth of each pass, will be changed in the future from uniform depth on all passes to a light cut on the last pass with the remaining stock evenly divided between the remaining passes. That would modify the time equation to sum over the passes instead of multiplying number of passes by time per pass. In the second equation c_r, cost of consumed tools, is currently set to zero, but in the future it could be picked up from a tool cost file. The costs for labor and machine, c_ℓ and c_r are taken from values entered by process planners in the machine tool file of the CPPP data base.

The only matter that has not been fully discussed so far is the method of determining the total cut depth that is used to calculate the number of passes and depth per pass. This method makes use of the current workpiece geometry, the operations matrix of Figure 25, and the CPPP data base machine tool file. The current workpiece geometry contains the current nominal dimension of the cut surface. The operations matrix tells in which operations the surface is cut and by what machine classes. The machine tool file gives the standard amount of stock removal of each machine class. If the cut in question is not the initial cut on the surface, the stock removal value from the machine tool file for that operation can be used directly. However, in the initial cut as much stock must be removed as is necessary to leave the proper amount for all subsequent cuts. So the standard stock removals for all subsequent cuts on that surface are summed up and combined with the final part dimension to determine what the dimension should be after the first cut. The difference between that dimension and the dimension before the cut gives the stock removal for the first cut on the surface.

The current CPPP system does require process planners to determine and put in the data base the standard or desired amount of stock removal for each machine class. Actual stock removals should depend also on the particular machine tool, the type of cut being made, the workpiece material, and its current hardness. CPPP could be enhanced to store and retrieve stock removal using these parameters to give more realistic stock removals.

2.3.6 Formulate Cutting Tool Combinations

Under consideration is a particular sequence of cuts on a particular machine tool. A list of candidate cutters have been determined for each type of cut. This means there are several possible combinations of cutter tools that can be used. Picking one candidate from each list gives a particular cutting tool combination. It is important to consider these combinations because on some machines the correct choice of the best tool for one cut, in theory, cannot be made without knowing the tools for the other cuts. For example, on a manual or NC machine it could be possible to reduce the total number of tools and save turret indexing time by using the same tool for more than one cut.

CPPP formulates the possible combinations and calculates the resulting operation time and cost for each. Essentially this builds up a subnetwork problem as shown in Figure 31. Proper evaluation of the network requires more data resources than are available in the demonstration CPPP. For example, if more than one tool is mounted on a single tool post to make multiple cuts at the same time, the recommended feeds must be adjusted to make them the same and equal to an available machine tool setting. After that, the cost of the tooling for the cuts is the sum of the tooling cost of each, but the total time is only the time of one single machine stroke. A similar situation arises when two separate tool posts operate simultaneously. However, CPPP cannot yet perform this analysis because it has no information on tool layout and simultaneous cutting.

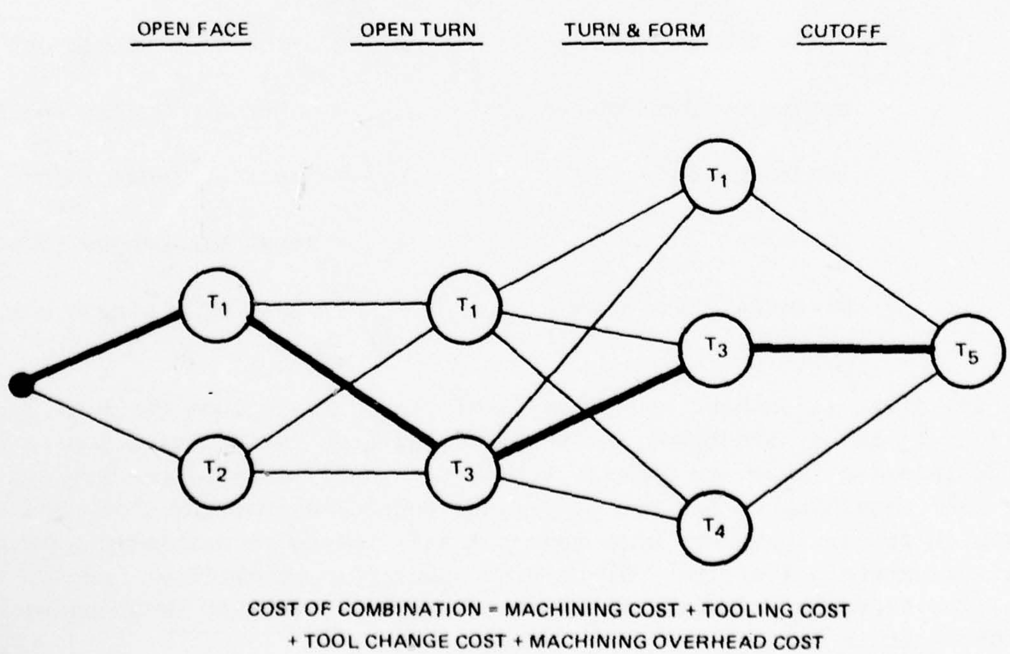


FIGURE 31. TOOL COMBINATION SUBNETWORK

When there *are no simultaneous* cuts, the cutting time for an operation with a particular sequence of cuts is the sum of all cutting times, turret indexing time, traverse time between cuts and tool setup time. To the cutting time CPPP adds machine setup time and part handling time to calculate an estimate of total operation time for that combination of tools on the machine tool. CPPP uses the total operation time for selecting the machine tool later on. Strictly speaking, only the cutting time is relevant to analysis of the tool combinations on a machine; the addition of a constant amount of noncutting time does not affect which combination is selected. Similarly, CPPP estimates the total cost of the operation for the tool combination being considered and not just the cutting tool. The cost of the operation includes the cost of cutting and noncutting time plus the cost of consumed tools and specially ordered durable tools. Durable tools include control cams and NC tapes as well as gauges and fixtures. This information is not all present in the current CPPP system. The actual formulas used are shown below.

$$t_o = t_s/L + t_t + t_i + t_p + \sum_{cuts} t_c \qquad \text{(per piece)}$$

$$c_o = c_d/L + (c_\ell + c_m) \cdot (t_s/L + t_t + t_i + t_p) + \sum_{cuts} c_c \qquad \text{(per piece)}$$

t_o	=	time of the operation	c_o	=	cost of the operation
t_s	=	setup time	t_c	=	time of a single cut
t_t	=	traverse time between cuts	c_d	=	cost of durable tooling
t_i	=	indexing time	c_ℓ	=	cost of labor ($/hr)
L	=	lot size	c_m	=	cost of machine ($/hr)
t_p	=	piece handling time	c_c	=	cost of a single cut

Costs are given in dollars and times in minutes. The values for time and cost of a cut, t_c and c_c are those previously calculated in Section 2.3.5. Traversing and indexing times are outside the current CPPP analysis and are set to zero. The remaining values are at present retrieved from the CPPP data base, into which process planners must insert actual values or estimated averages. In future extensions of the CPPP machining analysis capability, many of these, as well as traverse and indexing times, could be determined by standard time and cost calculations.

2.3.7 Select the Best Detailing of the Operation

So far this discussion of the CPPP detail planning cycle has descended in detail to the deepest level to analyze individual cutting tools. It has then stepped back up one level to analyze the use of a particular candidate combination of tools. This was all done for a particular cut sequence candidate on a particular machine tool candidate for the operation being detailed. These analyses are repeated many times to cover all combinations of alternate candidates. When each level of analysis is completed, CPPP makes a process decision. There are three levels at which decisions must be made.

1. Each candidate cut sequence may have several candidate tool combinations. When each tool combination has been analyzed and assigned time and cost estimates, the best tool combination is chosen. (The process planner must inform the system at the start whether he wants "best" to mean least time or least cost.) Its time, cost, and detailing information become the detail data for that particular candidate cut sequence and are saved while CPPP analyzes other cut sequence candidates.

2. After each candidate cut sequence has been analyzed by detailing its candidate tool combinations and selecting the best, CPPP selects the best cut sequence. The time and cost data for each are reviewed to find the best one. That sequence with its tools becomes the tentative detailing of the operation on that particular machine tool and is stored for later consideration. CPPP then repeats the detailing procedure on the remaining machine tool candidates.

3. When a cut sequence, tool combination, and the resulting time and cost have been determined for each machine tool candidate, CPPP selects the machine to use for the operation. Again this is the candidate with the lowest time or cost. The detailing on the chosen candidate becomes the final detailing of the operation.

This procedure of economic analysis is repeated for every metalcutting operation. Nonmetalcutting operations are handled similarly but much more simply because there is no cut sequence or cutting tool combination. When the last operation has been detailed, the detailed operation plan lacks only final dimensions and tolerances for the intermediate workpiece geometry of each operation. Subsequent subsystems of CPPP calculate dimensions and tolerances and produce the finished process plan. The methods used to calculate dimensions are described in the next section.

2.4 Calculation of Dimensions and Tolerances

The purpose of a process plan is to provide instructions to the workship telling how to make a part. A portion of the instructions for a machining operation specifies the machine to use, the tools to use, and the part features to machine. Another vital portion of the machining instructions gives the size of features and their location relative to some other features.

If each feature is machined only once and is machined after its location reference (datum) features have been machined, this is a rather simple matter. The part print dimensions can then be used directly. For example, the simple part in Figure 32 could be planned as follows:

Op. 10 - Size blank to dimensions A and B

Op. 20 - Cut left step to dimensions C and D

Op. 30 - Cut right step to dimensions C and E

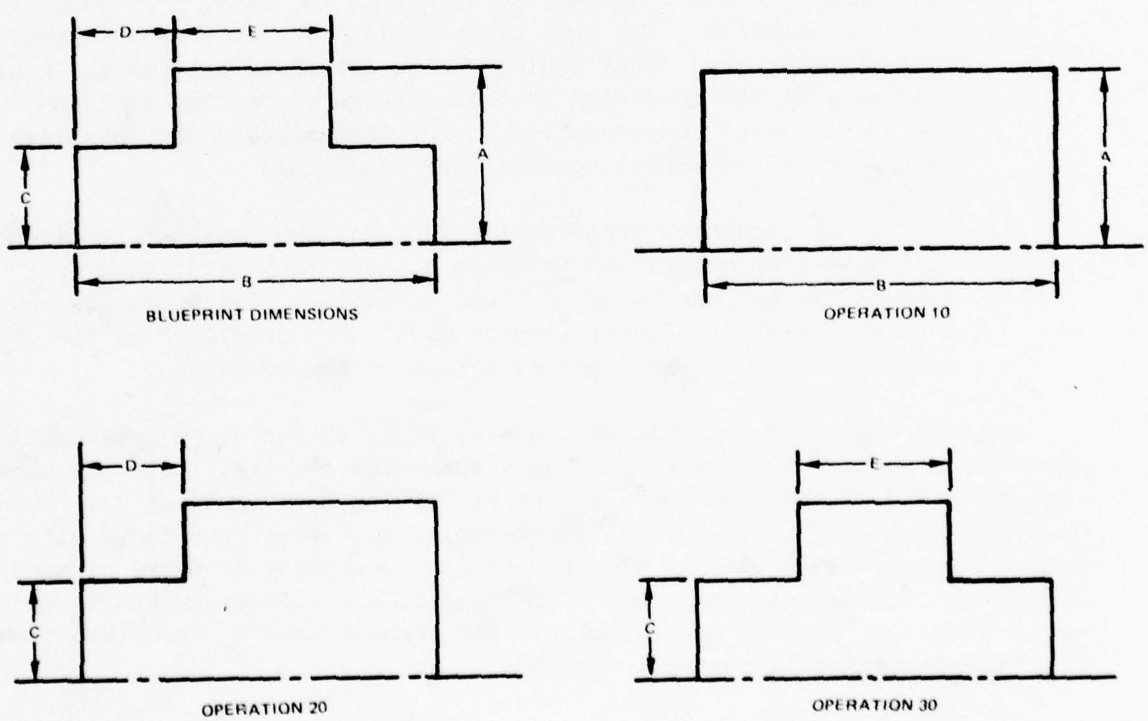


FIGURE 32 . MACHINING TO BLUEPRINT DIMENSIONS

However, if the right step is cut first it cannot be measured at dimension E from the left step, because that does not yet exist. The calculated dimension (D + E) must be used, as shown in Figure 33. This simple example illustrates the basic problem of workpiece dimensioning.

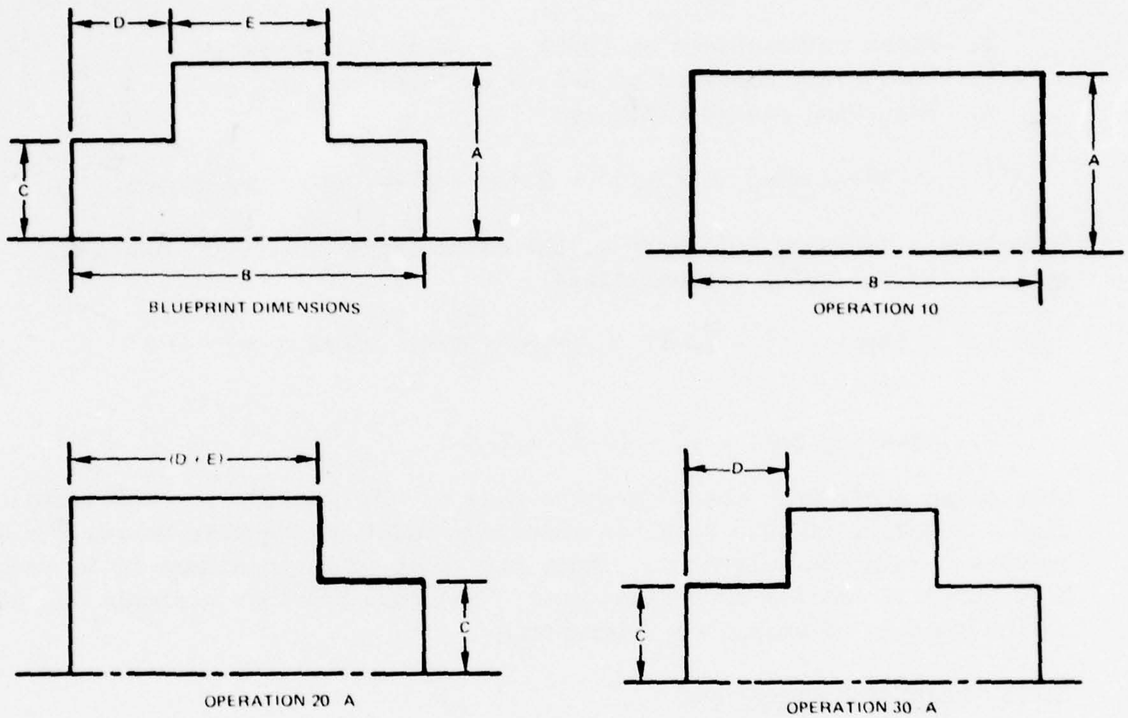


FIGURE 33. MACHINING TO CALCULATED DIMENSIONS

Dimensioning is only one aspect of locating; the other is tolerancing. It is impossible to achieve or to measure an exact dimension. The dimension "1 in." might be taken to mean less than one and one half inches, between 0.95 and 1.05 inches; etc. Manufacturing requires a more explicit statement of dimensional tolerance, usually in the form "C ± c". This means that the actual dimension must be between C-c and C+c. When tolerancing is applied to the example of Figure 32, Operations 20 and 30 above would be modified to use C ± c, D ± d and E ± e.

Now, if Operations 20-A and 30-A are used as in Figure 33, the calculation is more complicated. The toleranced step height is still $C \pm c$. The nominal dimension across the major diameter is still $(D+E)$, but what tolerance should be required? If $(D+E) \pm e$ were used for the cut on the right step and subsequently $D \pm d$ were used for the cut on the left step, the following "worst case" situation could result:

1. First cut machined to $(D+E) + e$ -- in tolerance
2. Second cut machined to $D-d$ -- in tolerance
3. Resulting flange width is

$$[(D+E) + e] - [D-d] = E + e + d \text{ -- out of tolerance.}$$

To maintain finished tolerance e, the machining tolerances t and $\hat{d}$ must satisfy the following inequalitites:

1. $[(D+E) + t] - [D-\hat{d}] = E+t+\hat{d} \leq E+e, \quad \text{where } \hat{d}<d$

2. $E-e \leq [(D+E) - t] - [D-\hat{d}] = E-t-\hat{d}$

This means $(t+\hat{d})$ must not be greater than e. In general, $t = e-d$ would be used. However, if this resulted in a very small or negative value, the machine could not hold the tolerance. Thus, the value of d would have to be reduced to $\hat{d}$ which is smaller than blueprint. This case provides a simple introduction to the problem of workpiece tolerancing.

2.4.1 Machining Diameters

Diameters present the most simple requirement for dimensioning and tolerancing. The dimension of an external diameter decreases by the amount of stock removal for the cut. The dimension of an internal diameter or a hole increases by the amount of stock removal. If the diameter is only machined once, the final dimension can be assigned directly from the part print. If machined more than once, its dimension on the final cut is the final part dimension. The dimension on previous cuts is determined by adding the stock removal back on for external diameters (or subtracting back off for internal diameters and holes).

For example, consider the following cuts on an external diameter:

Op. 20 - Rough turn	(from solid)
Op. 50 - Finish turn	.060 stock removal allowance
Op. 90 - Semi-finish grind	.020 stock removal allowance
Op. 110 - Finish grind	.010 stock removal allowance

If the final dimension were 2.000, then that is the value for Operation 110; and the previous values are 2.010 for Operation 90, 2.030 for Operation 50, and 2.090 for Operation 20. If this is the largest diameter and the part is made from 2.250 barstock, then the stock removed in Operation 20 is 0.160 inches off the diameter (0.080 off radius).

Since a diametral dimension is measured from one side to the other of a cylindrical surface or hole, there is no locating reference surface to worry about. Thus, there is no tolerance buildup problem. The tolerance on the final cut is the value on the part print. Any tolerances can be assigned to previous cuts provided they are consistent with machine tool capability and the desired amount of stock removal.

Figure 34 shows the relationship between tolerance and stock removal. Every cut starts with a previous dimension and tolerance, P ± p, and ends with a subsequent dimension and tolerance, S ± s. Stock removal is nominally the difference of the dimensions, R = P-S; but the actual stock removal may range anywhere from a maximum of (P+p)-(S-s) to a minimum of (P-p)-(S+s). It is bad practice to allow the *maximum* to get too large. It is absolutely essential to prevent the minimum from getting too small. Too much stock removal may result in excessive machining time. Too little stock removal

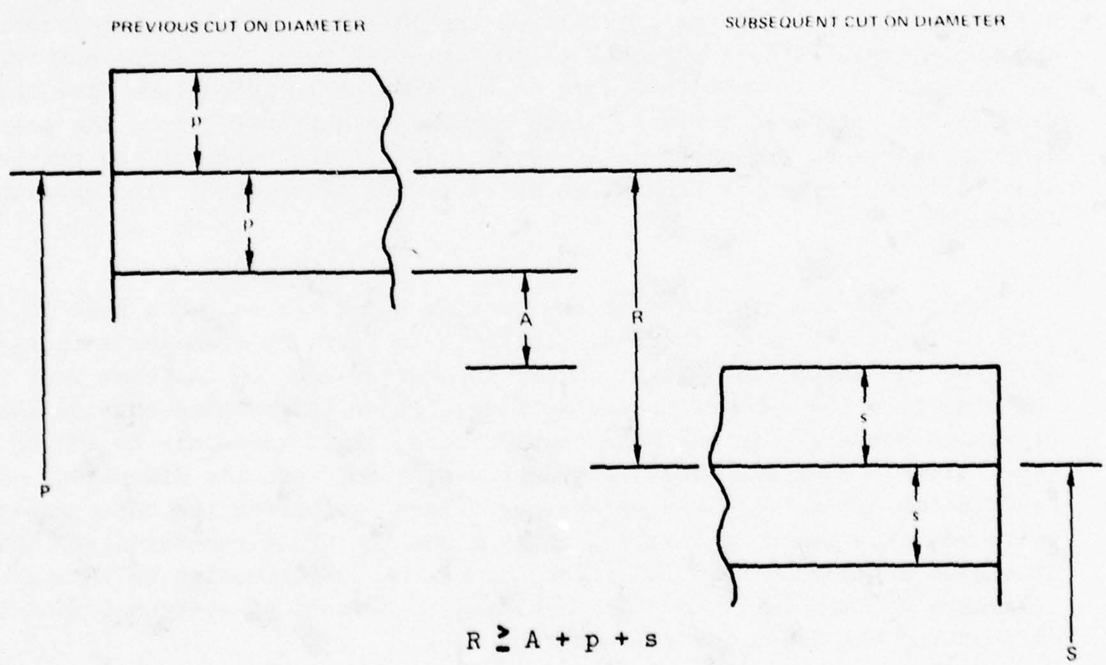


FIGURE 34. RELATIONSHIP BETWEEN TOLERANCE AND STOCK REMOVAL

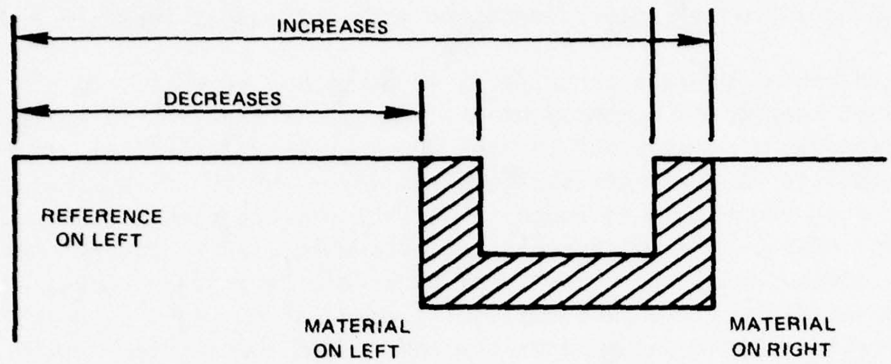
can result in bad surface finish or form conditions. Suppose A is the minimum actual stock removal required to remove scratches, correct for out-of-round, and insure cutting rather than plastic deformation of the workpiece by the tool. Then for automatic machines set to cut at a fixed diameter: $(P-p)-(S+s) \geq A$, i.e., $R = P-S \geq A+p+s$. (For manual machining using a fixed stock removal rather than a fixed cut diameter, it is only necessary that $(P-p)-(S-s) \geq A$ and hence that $R \geq A+p-s$.)

2.4.2 Machining Faces

Vertical part faces step from one diameter to another or from the end surfaces for cylindrical parts. Although faces follow the same general theory of dimensioning and tolerancing as diameters, they present additional difficulties.

Faces, like diameters, require coordination of nominal stock removal with tolerances to assure adequate actual stock removal. But calculating the lateral dimension of a subsequent cut from knowledge of its stock removal and of the dimension of the prior cut is different than for diameters. Whether the surface is external or internal makes no difference in the calculation for faces. Whether the stock removal is added or subtracted depends on the material side of the face and the position of the reference surface, as shown in Figure 35. Each part surface is a boundary between the part material on one side and air on the other. The material side of a face is "left" if the material is on the left and the air on the right, and the material side is "right" if the material is on the right and the air on the left. If the material side is the same as the direction from the face to its reference surface, stock removal is subtracted from the prior dimension because the distance is decreased. If the material and reference sides differ, the stock removal is added to the prior cut to increase the dimension.

This analysis of adding or subtracting stock removal on a face is only an introduction to the real problem. In fact, this analysis is valid only for the simple case in which two successive cuts on the same face are made from the same reference surface with no intervening cuts on that reference surface. In any more complex case, it is necessary to add or subtract several cuts and stock removals to find out what the dimension between the cut surface and reference surface was before the cut. After it is found, this prior dimension plus or minus the stock removal gives the dimension after the cut. The tolerance of the new dimension is the machining tolerance of that cut, plus the machining tolerances of every cut used in calculating the dimension prior to the cut.



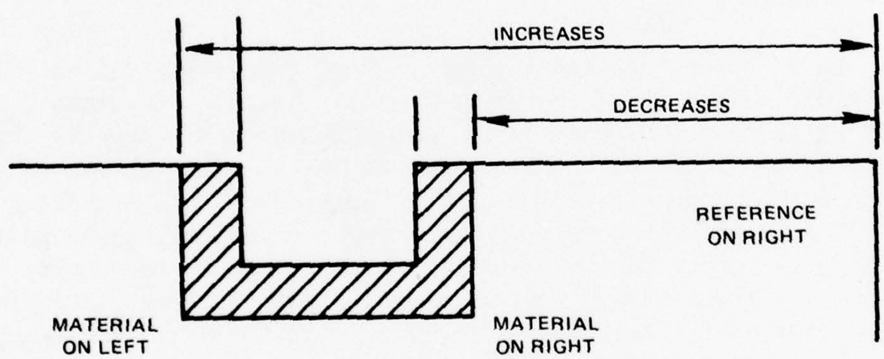


FIGURE 35. RELATIONSHIPS BETWEEN MATERIAL REMOVAL, REFERENCE SIDES AND DIMENSIONS. The increase/decrease of dimensions is shown as a function of material location and reference side.

The analysis of lateral dimensioning, for both the simple and complex cases, has proceeded forward from a prior dimension to a subsequent dimension. In practice, the calculations are mostly done backward, starting from the final part dimensions. So the formulas that result from the analysis are inverted to solve for prior dimensions when subsequent ones are known.

With manual process planning it is sometimes possible for the process planner to keep track mentally of all dimensions involved in calculating a prior-to-cut dimension and to make the correct calculation. However, this method is very susceptible to human error and is not well adapted to step by step checking. To remedy this, the process planner often uses a tolerance chart. The tolerance chart, shown in Figure 36, records each step in dimensioning and tolerancing of machining cuts on faces. On the form in the figure, the part outline is shown at the top, and each face has a vertical line running down the chart. In the middle section of the chart are arrows representing the machining cuts on faces, along with their operation number and machine tool. The arrowhead points to the cut face, and the dot is on the reference surface. At the bottom, the final dimensions from the part print are shown. These have dots at both ends, as they do not represent cuts.

Figure 37 shows the same tolerance chart completely filled out. Blueprint dimensions 24-27 correspond exactly to cuts 16-19 and have been "lifted" up to them. Dimensions 28-30 are not produced directly by a final cut and must be lifted up to balance lines 12, 14, and 10. (Note that cut 8 corresponds to dimension 29 but cut 13 intervenes thus requiring balance line 14.) A balance line represents a dimension calculated by adding or subtracting two other cut or balance lines above it in the chart. The lines that are involved and whether they are added or subtracted to produce the balance dimension are shown in the far right column. For example, balance 14 is the difference of cut 13 and balance 10, and balance 10 is the difference between cuts 6 and 8. Similarly, dimension 28 traces upward through balance 12, cut 11, and cut 8. Dimension 30 traces through balance 10, cut 8, and cut 6.

Balance lines 14, 12, and 10 result from determining the cuts involved in establishing the blueprint dimensions. Balance lines may also be be necessary to determine dimensions on nonfinal cuts such as 6 and 3, whose faces are finished in 13 and 11. The pair 6 and 13 does not need balance lines as it is the simple case of the same reference surface with no intervening cuts. The lines involved column shows 13=6-13 to indicate the length of 13 is the length of 6 minus the stock removal on 13. Balance 7 is needed to subtract cuts 3 and 6 in calculating cut 11.

By solving the "equations" like 13=6-13 or 14=13-10 that are implicit in the lines involved column, it is possible to calculate all intermediate

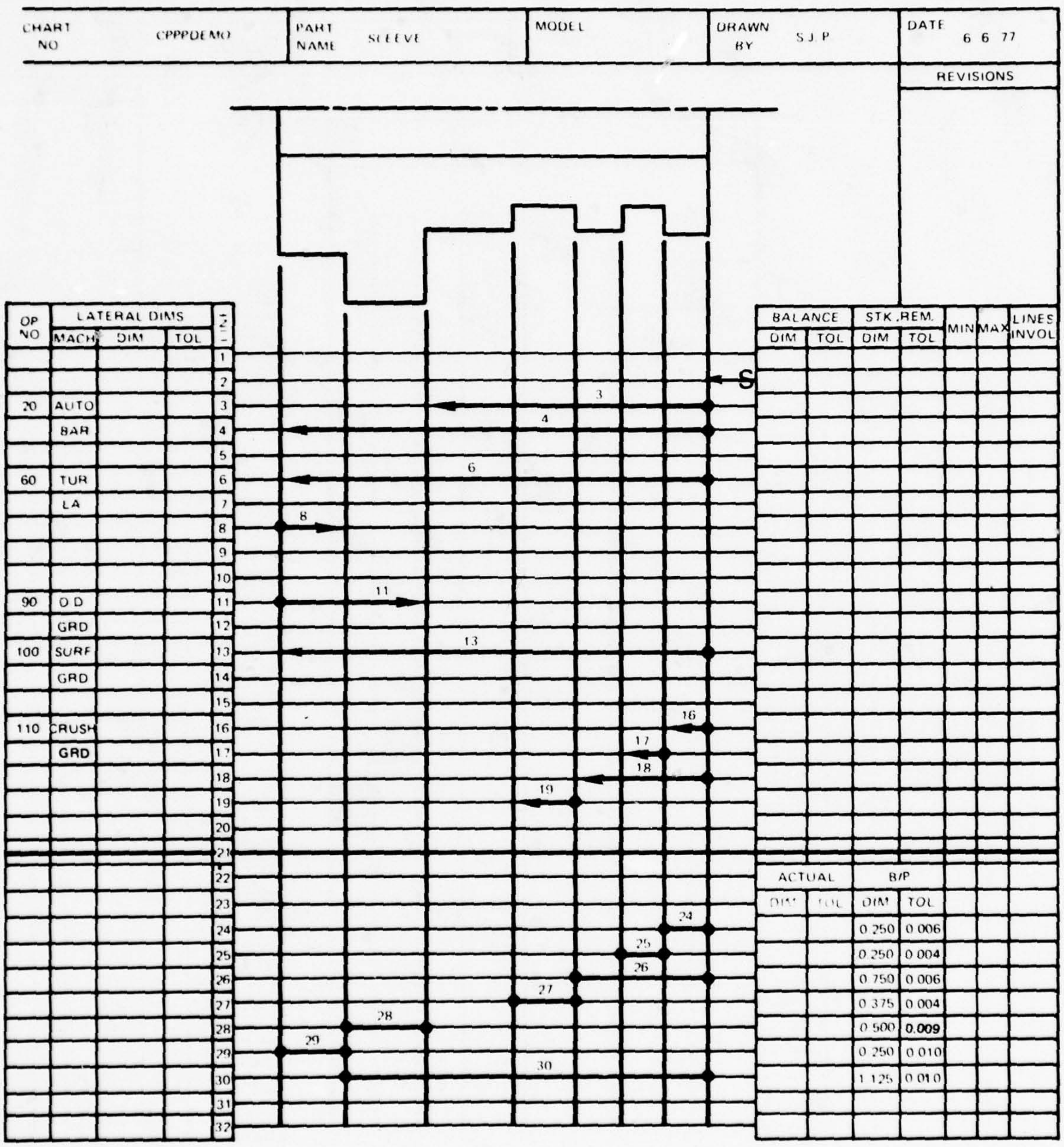


FIGURE 36. TOLERANCE CHART LAYOUT

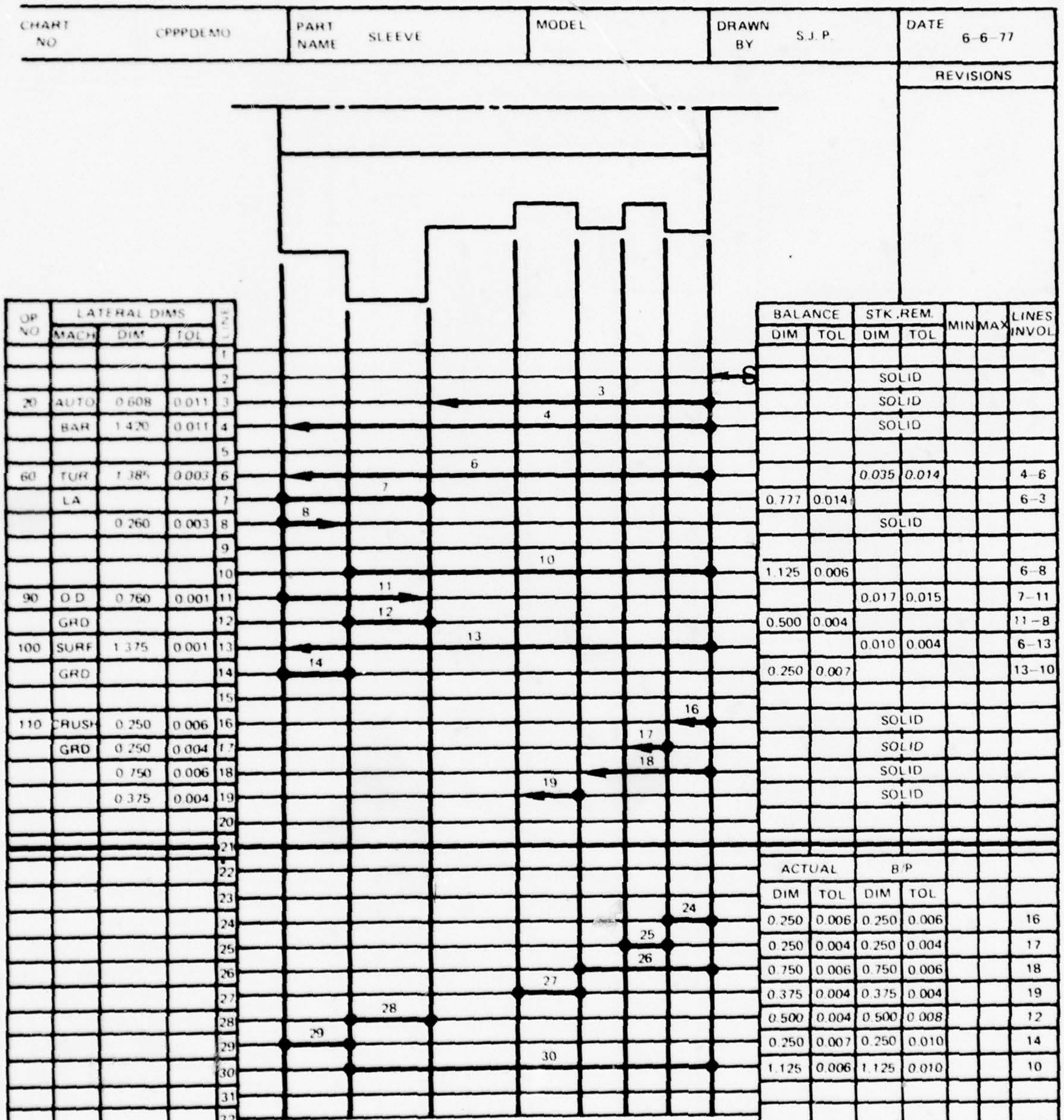


FIGURE 37. COMPLETED TOLERANCE CHART

workpiece dimensions. But what about the tolerances? There are three kinds of machining tolerances. Tolerances on cuts 16, 17, 18, and 19 come directly from the blueprint. Tolerances on cuts 6, 8, 11, and 13 combine to form blueprint tolerances on dimensions 28, 29, and 30. Tolerances on cuts 3 and 4 do not affect blueprint tolerances at all and can be chosen to minimize machining cost. The restricted but not totally determined tolerances, then, are 6, 8, 11, and 13.

Tracing through the lines involved gives the following three tolerance inequalities for solution:

$$30:\quad 10 \geq 6 + 8$$

$$29:\quad 14 \geq 13 + 6 + 8$$

$$28:\quad 12 \geq 11 + 8$$

The best solution is the largest set of tolerances 6, 8, 11, and 13 that satisfy the inequalities; but it is less important to have a large value for 13, which is a grind, than for the turning cuts. The method implemented by CPPP for solving the inequalities starts with fixed maximum tolerance values for grinding and for turning. Process planners must store in the CPPP data base values for these tolerances that are loose enough to be easily machined yet tight enough to keep stock removal small. The process planners also specify in the CPPP data base a tightest allowable tolerance for each type of machining and a step size by which the trial values are decreased from the starting value toward the tightest allowed value.

For example, suppose the grinding limits are .005-.001 with a step of .002; the turning limits are .011-.003 with a step of .004; and the blueprint tolerances are .010 for 30, .010 for 29, and .008 for 28. The initial trial values would be

$$30:\quad .010 \geq .011 + .011 \qquad = .022 \text{ (fail)}$$

$$29:\quad .010 \geq .005 + .011 + .011 \qquad = .027 \text{ (fail)}$$

$$28:\quad .008 \geq .005 + .011 \qquad = .016 \text{ (fail)}$$

Decreasing one step on both grinding and turning gives

$$30:\quad .010 \geq .007 + .007 \qquad = .014 \text{ (fail)}$$

$$29:\quad .010 \geq .003 + .007 + .007 \qquad = .017 \text{ (fail)}$$

$$28:\quad .008 \geq .003 + .007 \qquad = .010 \text{ (fail)}$$

Decreasing another step gives

$$30:\ .010 \geq .003 + .003 \qquad = .006 \text{ (pass)}$$

$$29:\ .010 \geq .001 + .003 + .003 \qquad = .007 \text{ (pass)}$$

$$28:\ .008 \geq .001 + .003 \qquad = .004 \text{ (pass)}$$

In this case the algorithm has failed to use the total tolerance in all cases because of the large step sizes in the example, but a solution was found. If the tightest allowable values do not result in a solution, something is wrong and manual intervention is required to improve the sequence of cuts or the selection of reference surfaces, or else to allow a tighter tolerance value.

In the discussion above on the tolerance chart, three areas were skipped over in order to concentrate on the mechanics of the chart. These are the selection of reference surfaces for each cut, the supplying of free tolerances, and the determination stock removals. The selection of proper reference surfaces is very important to the procedure because poor reference surfaces can lead to a drastic increase in tolerance build-up, i.e., more terms and larger values in the tolerance inequalities. The ideal situation is to use the blueprint reference surface for the cut reference when it is already finished and is a surface from which it is easy to locate and gauge the cut, but that is not the usual situation. Much work has been directed toward developing an algorithm to choose the best reference surface, but the initial implementation for CPPP simply chooses the free, unchucked end of the workpiece.

It is CPPP philosophy not to code into the programs any manufacturing values, so all tolerance and stock removal values used by CPPP in tolerance charting and dimensioning come from the CPPP workshop data base as supplied by the process planning staff. In particular the following values are used:

1. The free tolerance to use when the next cut is of the same type (e.g., turning followed by turning)

2. The free tolerance to use when the next cut is of a different type (e.g., turning followed by grinding)

3. The initial tolerance to use in tolerance inequalities

4. The tightest tolerance allowable in tolerance inequalities

5. The increment to use for the tolerance inequalities

6. The desired diametral and lateral nominal stock removals

7. The minimum actual diametral and lateral stock removals.

The first six of these are provided for the machine classes (lathes, ID grinders, hones, etc.); the last is provided for each specific machine tool. CPPP assigns the desired removal if it is large enough (or larger than necessary). Otherwise it adds the minimum actual value to the prior and subsequent tolerances to get nominal stock removal.

2.4.3 Machining Tapers and Contours

Even on parts whose surface can be generated by revolving a section around the part centerline, there can be surfaces other than diameters (circular cylinders) and faces (planes perpendicular to the centerline). Among these other surfaces are tapers, chamfers, countersinks, and drill points (all conical cylinders) plus concave and convex radii and more general contours. These are more difficult to dimension. They are also more difficult to generate and hence are usually finish cut from solid whenever possible. When they are cut more than once, the stock removal is generally a uniform band along the contour. They are usually dimensioned by gauge points (basic diameter with toleranced lateral position or basic lateral position with toleranced diameter) or by a series of points on the surface (each point being a lateral X position and a diametial or radial Y position).

The points on a contour can be dimensioned and toleranced much as any other point, except that the change in diameter or lateral position will be greater than the stock removal. This is because diameters are measured vertically and lateral positions horizontally, while the stock removal for a contour is measured neither vertically nor horizontally but perpendicular to the contour. For tapers and radii the resultant change can be calculated by plane geometry and trigonometry. More general surfaces require some sort of formula for the contour.

Another complicating feature of contours is that they change position when their adjacent surfaces are cut. This is to some extent true of simpler surfaces, for example, a face gets shorter when the diameter above it is cut. But it is of no concern there because the single dimension of interest (the lateral position of a face or diametral value of a diameter) does not change when the adjacent surface is cut. A contour is often partially, or in the case of a tapered surface completely, determined by both the lateral position and diametral value of its intersections with its neighbors. For example, chamfers are often dimensioned by width and height, and whenever the adjacent face or diameter is machined the chamfer gets shorter.

The CPPP system now in the demonstration phase has concentrated on using stored process logic to determine operations in the initial planning cycle. Substantial work has been done on the remainder of the system, but the dimensioning and tolerancing areas are not yet complete. While the tolerance charting code works for faces and diameters, it is still in the process of being extended to tapered surfaces and contours.

2.4.4 Stock Growth and Distortion Processes

It is known that there are operations such as plating, coating, and hardcoating in which the entire part surface grows outward by some uniform amount. This growth has a process tolerance just as each cut has a machining tolerance. However, CPPP is not yet equipped to dimension and tolerance stock growth operations. It is also not equipped to refigure tolerances after stress relief and other processes that result in part distortion but have no predictable change in nominal dimensions. These are areas for future work following the addition of tapers and contours to the tolerance charting subsystem.

2.5 Man-Machine Communications

Fully automated process planning for the full spectrum of machined parts is beyond the capability of current technology -- and will remain so for years. It is therefore necessary that a computerized process planning system offer a convenient, effective means of human oversight and intervention. This section describes the CPPP capability for man-machine communication. Appendix B gives detailed documentation and illustrations of CPPP's interaction capabilities.

2.5.1 The Process Planning Terminal

The CPPP communication medium is a low cost terminal with line-drawing and text capabilities that can be located away from the computer in the process planning area. CPPP has been designed so that no computer skills are required for the process planner to operate the system and process planning, as seen by the user at the terminal, progresses in a familiar manner. Part sketches are heavily used to communicate the status and progress of planning. Communication is conversational. Response to user input ranges from almost instantaneous to a few seconds if adequate computer support is provided. Several levels of interaction are available -- the process planner can choose among these according to the completeness and correctness of the manufacturing data base, his confidence in CPPP, and his own work habits.

The terminal is connected to a general purpose computer system on which CPPP is implemented. In response to directions input at the terminal, the

computer system accesses data in the manufacturing data base, uses this data to execute CPPP code, transmits graphic displays which inform the process planner of the status of planning and options available to him, and stores the process plan data that are generated. CPPP is currently implemented for TEKTRONIX 4006, 4010, 4012, and 4014 graphic terminals. These may be connected to the computer by voice-grade (telephone or intercom) lines or by more specialized lines. The terminal may be very close to or distant from the computer.

2.5.2 CPPP Modes of Operation

The process planner can choose among three CPPP modes of operation which offer different degrees of user involvement. Confidence in the CPPP data base, especially process decision models, will usually determine the desired mode.

The highest level of automation is fully automatic process planning. In this mode CPPP uses coded manufacturing rules, other manufacturing data, and part designs to generate complete process plans without human intervention. Most obviously, this level is used to prepare process plans when there is full conficence in the system. When confidence is less than total, it may be practical to use this mode to generate a "first pass" plan which can be studied before generating a final plan and also for make-or-buy, producibility, and cost estimating studies.

If the data base is somewhat less than complete or there is not full confidence in its correctness, semiautomatic process planning is appropriate. In this mode, process planning is performed by CPPP with the user overseeing and, to the extent desired, modifying the plan as it is developed. The user may select the degree of supervision he wishes to exercise by specifying the points at which he desires to interact with the system. (See the discussion of interaction points below.)

When process decision models are unavailable or the process planner wishes to investigate radically different processes, interactive process planning may be used. In this mode the user supplies the sequence of operations, after which the system helps to provide a detailed plan for each operation. As with the semiautomatic mode, various degrees of interaction are available.

2.5.3 Interaction Points

There are fifteen major points where the user can interact with CPPP. To describe the role of these interaction points, a skeletal review of the system's processing is appropriate. Figure 38 gives a high level view. The process planner initiates a CPPP session by entering basic data and instruc-

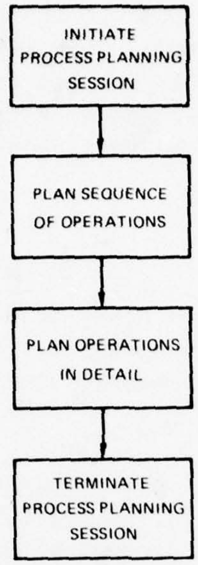


FIGURE 38. OVERVIEW OF CPPP

tions. A sequence of operations is then produced (Section 2.2). For each operation, operation type, machine class(es) or particular machine tool, setup orientation, and surfaces to be affected are determined.

When the sequence of operations is complete, each operation is planned in detail (Section 2.3). Alternative machine tools are identified. For each machine tool, alternative cut sequences are generated. For each cut in each sequence, alternative tooling is identified. The operation is then planned for various tooling combinations, with time and cost calculated. The best tooling combination for each cut sequence, then the best cut sequence for each machine, then the best machine for the operation are chosen. The detailed plan for that operation is then stored and the next operation attacked in the same manner. Once all operations have been planned in detail, the process plan is complete and the planning session is terminated.

Two interaction points occur in CPPP initiation (Figure 39).

1. Initiate Method of Process Planning. The process planner enters his name, part number, and the desired method of process planning. In the present system he may choose to generate a new plan, either by using process decision rules or by defining operations manually. Resumption of a par-

tially completed plan or editing of a completed plan could be offered in the future.

2. Initiate Startup Data for a New Plan. The process planner gives lot size and the economic criterion to be used for decision making (cost or time). He selects the interaction points he wishes to use and the operations for which he wishes interaction.

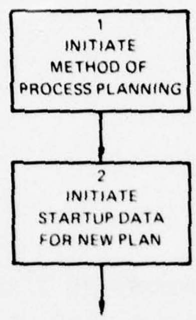


FIGURE 39. INTERACTION POINTS IN CPPP INITIATION

Three interaction points are available in planning the sequence of operations (Figure 40).

3. Accept/Modify Generated Operation. The data and workpiece sketch of an operation generated by a process decision model are displayed. The user may modify the operation in several ways: adding or removing surfaces/features, changing the machine class(es) to be considered, changing the setup orientation, etc. The operation may also be entirely rejected.

4. Interactively Define Operation. A process planner can use this interaction point to define a sequence of operations without using a process decision model. The user would specify the type of operation, machine tool or machine tool class, and surfaces to be cut in a metal removal operation. This method of operation would continue until a full sequence of operations had been specified.

5. Accept/Modify Sequence of Operations. The sequence of operations can be reviewed at this interaction point. The process planner has several options available: delete an operation, add an operation, modify an operation, or accept the sequence of operations.

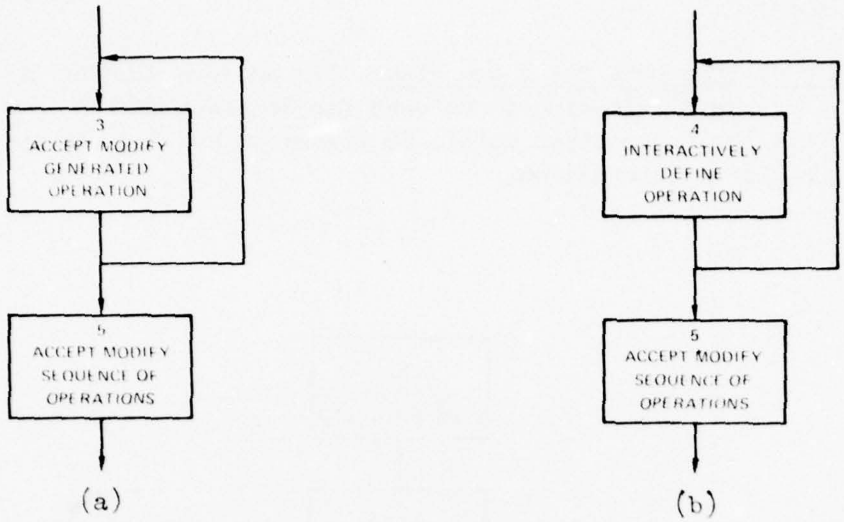


FIGURE 40. INTERACTION POINTS IN PLANNING SEQUENCE OF OPERATIONS. If operations are generated by process decision rules, (a) is applicable. Interactive planning is shown in (b).

Detailed planning of operations offers a number of opportunities for interaction by the process planner (Figure 41).

6. Accept/Modify Machine Tool Candidates. The process planner may specify additions or deletions to the machine tool candidates selected by CPPP for possible use in an operation.

7. Accept/Modify Cut Sequence Candidates. The candidate cut sequences selected by CPPP to remove stock in an operation are displayed. The user may add or delete candidate sequences.

8. Accept/Modify Cutting Tool Candidates. The candidate cutting tools (or tool types) selected by CPPP for each cut are displayed. Tools may be deleted or new ones specified.

9. Accept/Modify Machining Data. Machining data (e.g., depth of cut, number of cuts, feed, speed, time, tool life, tool material, horsepower) determined for each type of cut and tool are displayed.

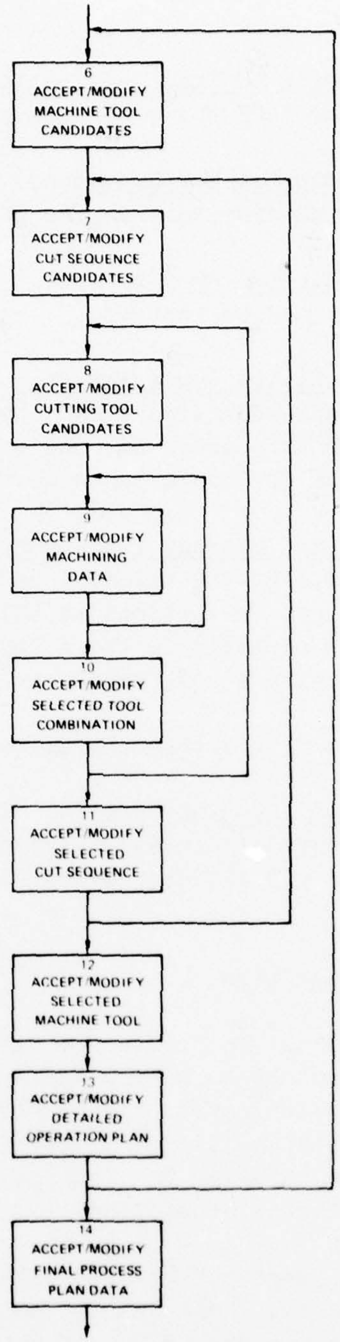


FIGURE 41. INTERACTION POINTS IN PLANNING OPERATION DETAILS

10. Accept/Modify Selected Tool Combination. The combination of cutting tools selected by CPPP for a candidate cut sequence may be changed.

11. Accept/Modify Selected Cut Sequence. The cut sequence selected by CPPP for a candidate machine tool may be changed.

12. Accept/Modify Selected Machine Tool. The machine tool selected by CPPP for an operation may be changed.

13. Accept/Modify Detailed Operation Plan. The detailed plan for an operation is displayed, identifying the chosen machine tool, cut sequence, and tools. The process planner has the option to accept the operation as planned or replan the operation with full interaction.

14. Accept/Modify Final Process Plan Data. The entire process plan can be reviewed in detail at the terminal before it is printed by CPPP. The process planner has few options at this point in the present system. Enhancements can be added in the future that will enable a process planner to selectively add, delete or modify operations.

Termination of a CPPP session involves a single interaction point.

15. Terminate Process Planning Session. The process planner has the option to request the type of process planning documentation to be produced by CPPP. It can be the sequence of operations (summary sheet), operation sheets, or both.

2.5.4 Levels of Interaction

Most of the interaction points described above are optional. The process planner may choose whether to review and accept/modify the CPPP decision which precedes each interaction point. If he elects interaction, a graphic display is shown which exhibits the decision and offers options for viewing additional data and modifying or changing the decision. If not, the display is by-passed and CPPP proceeds without interaction.

The interaction points associated with initiating and terminating a process planning session (1, 2 and 15) are not optional. Interaction at these points is required to operate CPPP. If fully automated planning is requested no other interaction points are used. Interaction point 4 is mandatory if the interactive process planning mode is requested. Otherwise, the process planner may choose whatever combination of the remaining points (3, 5 through 14) he desires.

3.0 BENEFIT ANALYSIS

Analysis of the benefits of computerized production process planning was performed as three tasks. First, benefits to metalcutting industry in general were analyzed. In this effort, alternative computer capabilities were considered. The second analysis was a case study of benefits of the demonstration CPPP system to the Hamilton Standard Division of United Technologies Corporation. Third, benefits of CPPP were projected to industry producing Army missile components and other defense items.

3.1 General Industry Benefits[1]

A survey was mailed to 153 metalcutting companies. Data on process planning methods, associated costs, and the expected savings/costs of computerized process planning were requested. The response to the survey was used as the basis for an analysis of benefits of the technology.

3.1.1 Industry Survey

The survey consisted of three sections. The first section described the purpose of the survey and provided definitions needed to complete it. The second section requested information which would characterize the company, its products, and other relevant parameters--process planning methods and costs, current and planned usage of computer aids to process planning, machining costs, tooling costs, etc. In the third section, three different levels of process planning automation (Systems 1, 2 and 3) were described. Each company was asked to estimate benefits over manual process planning, implementation costs, operating and maintenance costs, and obstacles to implementation for each system.

System 1 provides a capability to retrieve process plans using part classification coding or group technology. The system also helps produce process plan documentation. Every machined part is assigned a code number which classifies its geometry and machining requirements. The code is used to access computer-maintained data files that can be examined by a process planner to ascertain whether the process plan of a given part is currently available, can be prepared by modifying an existing process plan for a similar part, or must be created from scratch. The planner uses the information uncovered when manually producing a process plan for the part. Once the process plan is manually prepared, the machining and other process steps are coded into the computer by keypunch operators. The computer produces hard copy documents for the shop.

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[1]The work reported in this section was largely performed by the IIT Research Institute.

System 2 offers the capabilities of System 1 plus interactive modification of existing plans, automatic determination of machining parameters (feed, speed, etc.) and times, and automatic documentation (without workpiece sketches). It contains a computerized data base which allows the retrieval of lists of parts belonging to the same part family, standard process plans for a particular family and process plans for an existing part number.

System 3 provides semi-automatic process planning with computer generation of operations. This system is considerably different from the previous systems in several respects. One of the major differences is that it has a generative process planning capability. The system contains decision logic concerning process planning. It can produce most or all of the process plan for a specific part without relying on modification of a standard process plan for a similar part. (However, this system could also operate in the same mode as System 2.) System 3 has an extensive data base containing process decision logic, machine data, tooling data, and machinability data. The process planner may use a graphic terminal to review and modify the system's planning. Documentation is automatically produced.

3.1.2 Response to Survey

Twenty-one companies responded to the survey (Table 3). Four are missile prime contractors or subcontractors, eight are nonmissile aerospace companies and nine are nonaerospace.

TABLE 3. COMPANIES RESPONDING TO GENERAL INDUSTRY SURVEY

ACF Industries, WKM Valve Div.
Beckman Instruments
Bell Helicopter
Boeing Commercial Airplane Company
Borg-Warner
Deere & Company
Fairchild Republic
General Dynamics, Pomona Div.
Giddings & Lewis Machine Tool
The Gillette Co.
Hughes Aircraft
International Harvester
Lockheed-Georgia
Lockheed Missile & Space
Midland-Ross Corp., Surface Combustion Div.
Sundstrand Aviation, Div. of Sundstrand Corp.
United Technologies, Chemical Systems Div.
United Technologies, Hamilton Standard
United Technologies, Sikorsky Aircraft
Vought Corporation, Michigan Div.
Westinghouse Electric Corp., Large Turbine Div.

The survey requested estimates of the percentage of total value of products shipped which represents machined parts. Also, information was requested which could be used to determine the fraction of machined parts manufactured in-house. Average responses are shown in Figure 42. Roughly one-quarter of the cost of products is in machined parts. Cylindrical parts account for more than half this portion. About three quarters of machining is done in-house.

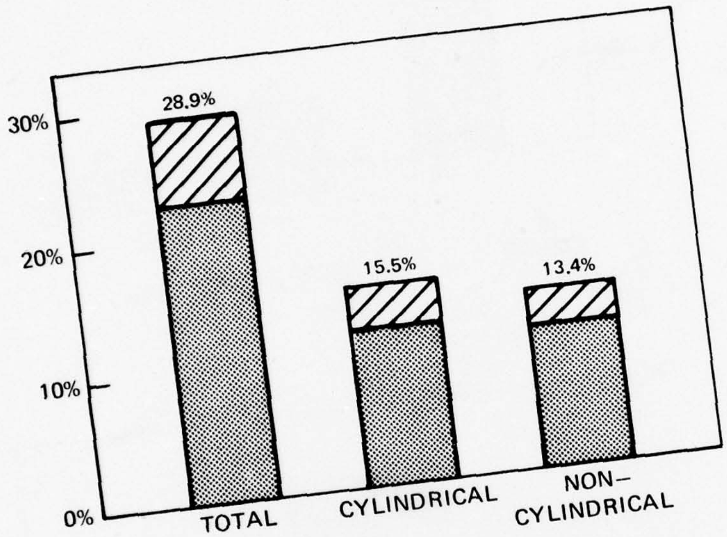

FIGURE 42. MACHINED PARTS AS A PERCENTAGE OF PRODUCT VALUE Full shading represents parts fabricated in-house. Partial shading shows purchased parts.

Several questions were asked concerning lot sizes and number of lots per year. Figures 43 and 44 summarize the results for cylindrical parts. (Noncylindrical results did not differ significantly for this question or for others discussed below. Therefore, only responses for cylindrical parts are presented.) The typical part fabricated by a respondent is made in lots of less than 100 pieces, with two to ten lots produced per year. Aerospace respondents generally produce fewer and smaller lots than nonaerospace.

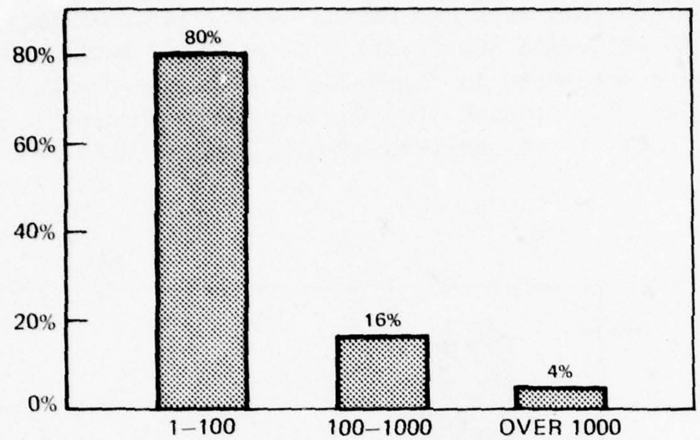

FIGURE 43. LOT SIZE DISTRIBUTION

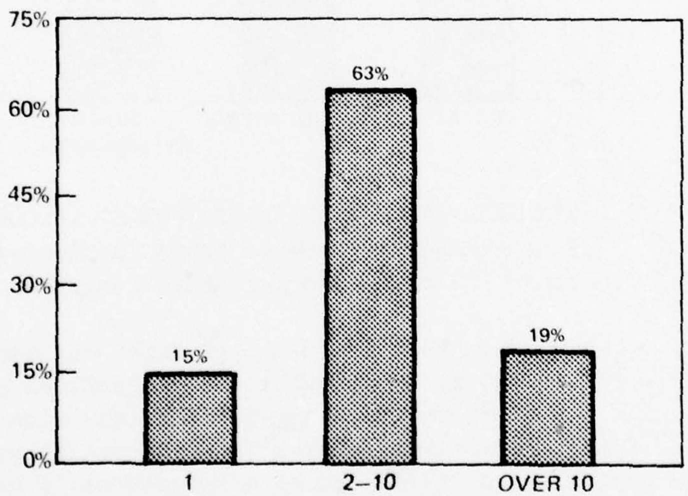

FIGURE 44. NUMBER OF LOTS PER YEAR FOR A PART
Some responses did not total to 100% because parts not made in a year were included.

The survey requested estimates of the portion of manufacturing costs for parts produced in-house which were attributable to process planning, direct labor, material, tooling, scrap and rework, and overhead and profit. The average responses are shown in Figure 45. There was considerable variation in responses to this question. Process planning costs were generally higher for missile and other aerospace manufacturers than for nonaerospace companies.

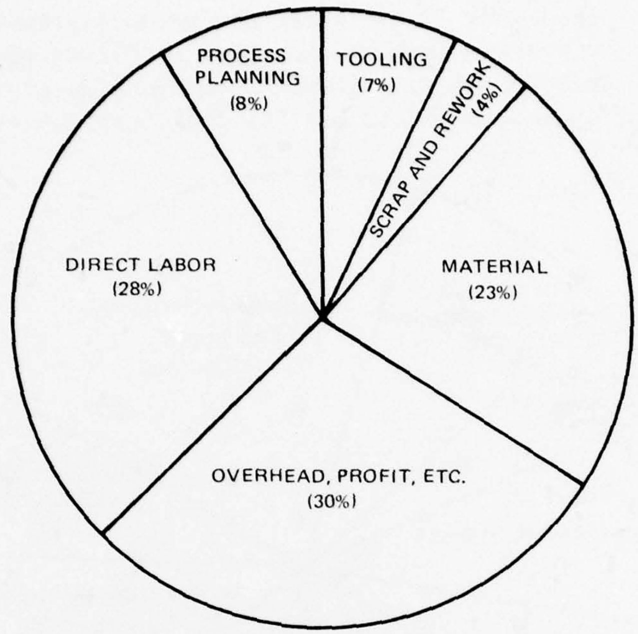

FIGURE 45. BREAKDOWN OF MANUFACTURING COST FOR MACHINED PARTS. The chart shows average response to the general industry survey.

Process plan preparation can be divided into three activities: planning for a new part, modification of existing plans, and planning for study purposes (cost estimates, make/buy studies, producibility analyses). Table 4 shows relative frequency and costs for the three activities. The survey showed that aerospace manufacturers expend a larger portion of process planning costs for studies (20 percent vs. 5 percent for nonaerospace companies).

TABLE 4. TYPES OF PROCESS PLANS AND THEIR COSTS

Type	Frequency	Average Cost
Plan for New Part	39%	$492
Modified Plan	39%	$166
Study Plan	22%	$124

A functional breakdown of costs for new process plans was also requested in the survey. The average response is shown in Figure 46. Costs are well distributed over the various functions. Determination of operation sequences and preparation of operation sheets are the costliest activities.

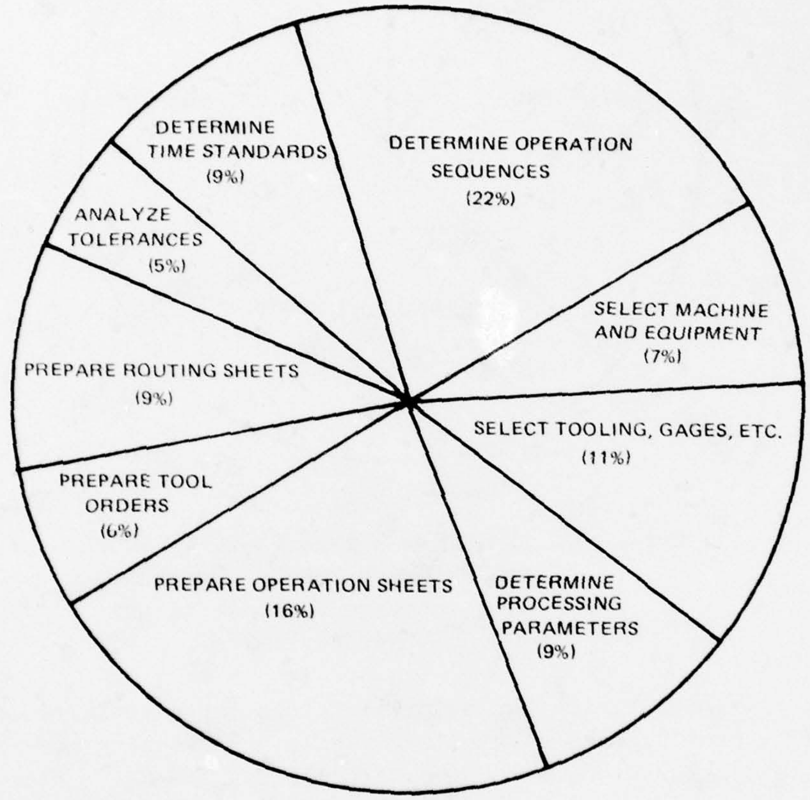

FIGURE 46. BREAKDOWN OF PROCESS PLANNING COSTS FOR NEW PROCESS PLANS. The sum of the component costs is less than 100% because some respondents included other functions.

The responses to the survey clearly indicate that industry is receptive to computerized process planning. Many respondents are currently using some form of computer assistance. A majority said they plan to introduce new aids or increase the scope of current ones in the next two years.

A major portion of the survey was devoted to the potential impact of the three computerized process planning systems. Given a description of the systems, the recipients were asked to estimate potential savings and costs to implement and maintain the systems. They were also requested to evaluate intangible benefits of the systems.

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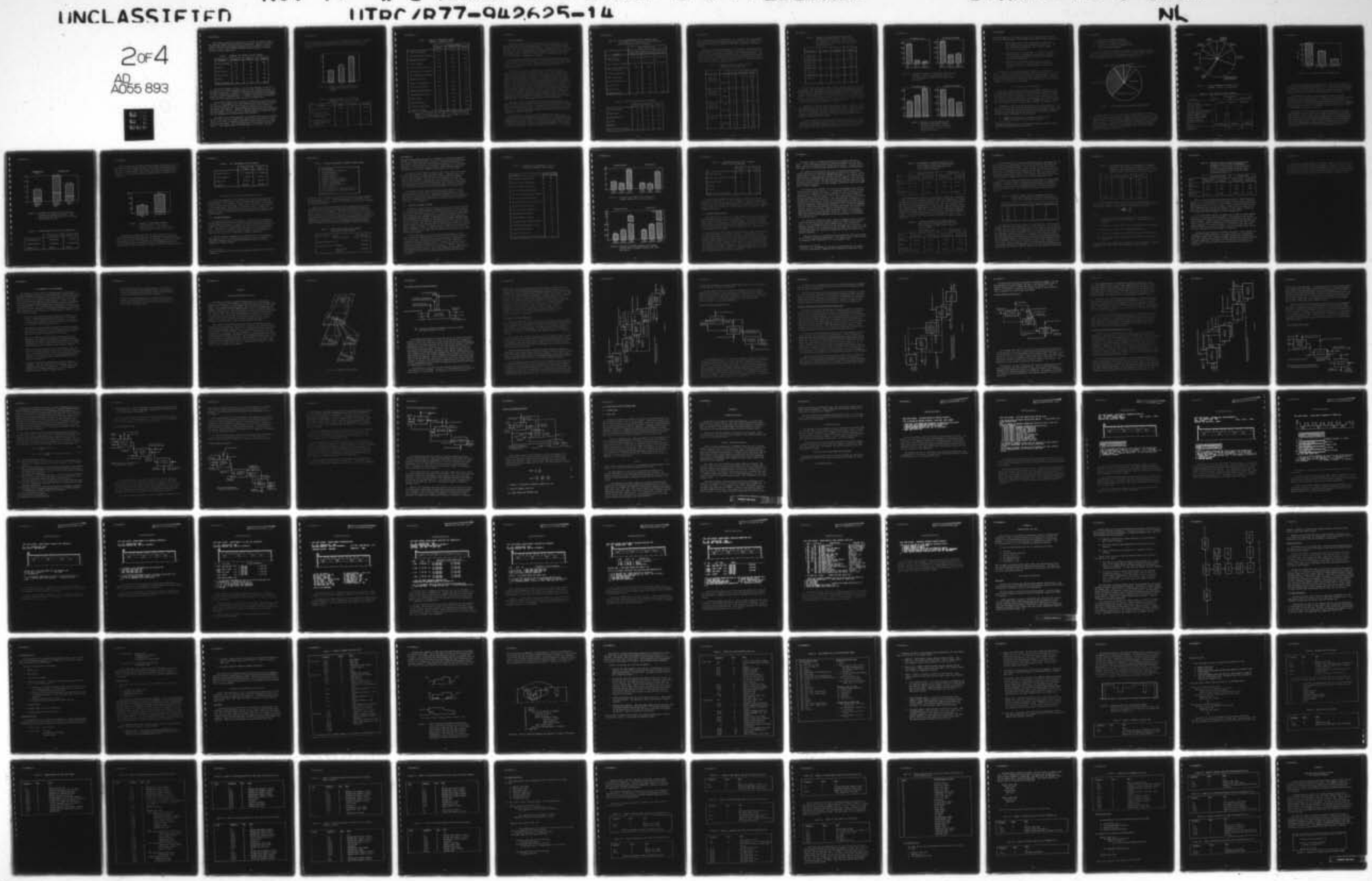

The average estimated cost savings for the systems are shown in Table 5 The potential savings for each system are significant. System 1, the least sophisticated from a technological standpoint, had the smallest potential savings. Systems 2 and 3 showed increasing savings potential, in keeping with their greater capabilities.

TABLE 5. POTENTIAL COST SAVINGS FOR CPPP SYSTEMS

Cost Area	System 1	System 2	System 3
Process Planning	28%	39%	58%
Material	3%	3%	4%
Direct Labor	5%	7%	10%
Scrap & Rework	4 %	6%	10%
Tooling	5%	7%	12%
Work in Process	2%	4 %	6%

The savings estimates of Table 5 and the cost breakdown of Figure 45 were merged to calculate estimated savings in overall fabrication costs. The projected savings were 4.3 percent, 6.5 percent, and 9.6 percent for Systems 1, 2 and 3, respectively (Figure 47). It should be noted that the calculation assumed no impact on overhead costs. In practice, reductions in nonoverhead costs should be accompanied by some reduction in overhead costs.

The average estimated costs to install and maintain the systems are shown in Table 6 . Most companies felt that hardware such as interactive terminals and interface equipment would be required for Systems 2 and 3; however, it was apparent that costs for complete computer installations had also been included in some responses. Therefore, average hardware costs were much higher than anticipated. In all cases, as the systems became more complex and powerful, the implementation and maintenance costs increased.

The impact of the three systems in less tangible areas was also evaluated. In the first survey, the companies were asked to rate each system on a scale from -2 to +2, with -2 implying a significant negative impact and +2 a significant positive impact. The average responses for each system are shown in Table 7 . Each system showed a favorable impact in all areas. The most

favorable impacts were in increasing the uniformity of process plans, reducing process planning leadtime and improving cost estimating procedures. The increase in expectations from System 1 to System 2 to System 3 is readily apparent.

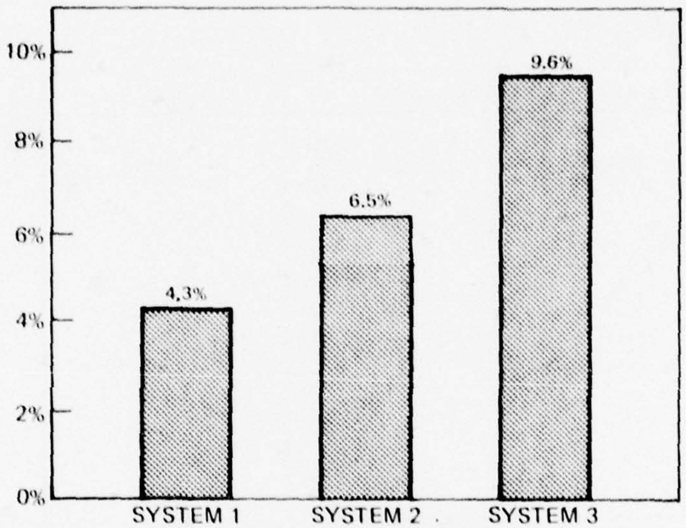

FIGURE 47. ESTIMATES OF OVERALL FABRICATION COST SAVINGS FROM COMPUTERIZED PROCESS PLANNING

TABLE 6. AVERAGE ESTIMATED INSTALLATION AND MAINTENANCE COSTS FOR CPPP SYSTEMS

Cost Area	System 1	System 2	System 3
Hardware (nonrecurring)	$40 K	$117 K	$244 K
Establish Data Files, Training and Testing (nonrecurring)	51	148	367
Program Maintenance and Updating Data Files (recurring)	39	56	103

TABLE 7. IMPACT OF COMPUTERIZED PROCESS PLANNING IN INTANGIBLE AREAS

	Average Ranking		
	System 1	System 2	System 3
Production Leadtime	0.86	1.30	1.47
Process Planning Leadtime	1.24	1.55	1.89
Machine Utilization	0.57	0.85	1.41
Product Quality	0.38	0.45	0.79
Direct Labor Utilization	0.48	0.45	1.00
Uniformity of Process Plans	1.48	1.70	1.89
Cost Estimating Procedures	1.14	1.32	1.79
Make/Buy Decisions	0.76	1.56	1.33
Product Standardization	0.81	1.16	1.33
Critical Labor Skills	0.29	0.37	0.78
Material Standardization	0.57	0.68	0.89
Producibility of Parts	0.55	0.65	1.11
Plant Layout	0.43	0.65	0.84
Material Handling	0.62	0.79	1.06
Production Scheduling	0.80	0.95	1.37
Capacity Planning	0.80	1.00	1.37

*Ranked on a scale of -2 to +2, where -2 = significant negative impact, -1 = slight negative impact, 0 = no change, +1 = slight improvement, +2 = significant improvement.

3.1.3 Benefit Analysis

Cost benefit analyses were conducted using a discounted cash flow model. The analyses were for a ten-year period and took into consideration implementation costs, recurring costs and savings. A 10 percent discounting rate was used. The model also assumed a 48 percent corporate tax rate, a 7 percent investment tax credit and depreciation of hardware costs by the sum-of-the-years-digits method. Annual cash flows, return on investment, benefit-to-cost ratio and years to payback were computed.

A sensitivity analysis was performed by independently varying each of 17 input variables by +10 percent and -10 percent. The impact of these changes on benefit-to-cost ratio, years to payback and return on investment was then computed to determine those factors which have the largest impact on economic performance.

The response to the data survey was used to define three "model" manufacturing environments for benefit analysis. The model companies were defined in terms of annual product value, fabrication cost breakdown, and degree of part similarity. The three are descriptively termed (1) a small manufacturer with high part similarity, (2) a medium-size manufacturer with fair part similarity and (3) a large manufacturer with high part similarity. Table 8 gives the definitions of the three environments. The three environments were extracted from the survey response by an informal clustering process. In this process, some of the data provided by a few respondents were not used because they were clearly unrealistic and/or failed cross-checks built into the survey. For example, two respondents reported overhead costs to be zero and two gave estimates of process planning costs that appeared unrealistically high and were incompatible with other answers they gave. Comparison of the cost breakdown in Figure 45 with the definitions of Table 8 shows the effect of not using a small fraction of the survey data.

The costs to install and maintain the systems and the potential cost reduction factors were estimated for each of the three manufacturing scenarios. The cost reduction factors used in the analyses are given in Table 9 . These are in close agreement with, but not identical to, the response to the survey (Table 5). The small differences between the two reflect the Contractor's assessment of the three systems.

The survey did not request a detailed implementation plan for each system. Furthermore, the respondents' estimates of total implementation and maintenance costs varied greatly. Therefore, the costs of implementing and maintaining the systems and the rate at which the ultimate benefits of Table 9 could be achieved were based on the Contractor's judgment. No software development or purchase costs were included in the analysis. It was assumed

TABLE 8. TYPES OF MANUFACTURERS USED IN BENEFIT ANALYSIS
The parameters below were used for both cylindrical and noncylindrical cash flow analyses.

	Type of Manufacturer		
Parameter	Small/Highly Similar Parts	Medium/Fairly Similar Parts	Large/Highly Similar Parts
Annual Value of Parts Produced	$5 Million	$10 Million	$50 Million
Work in Process Inventory	$2.5 Million	$ 6 Million	$25 Million
Parts Impacted by System (By Dollar Value)	90%	80%	90%
Process Planning Costs	4%	5%	3%
Direct Labor Costs	27%	20%	25%
Scrap and Rework Costs	2%	3%	2%
Tooling Costs	7%	7%	5%
Material Costs	15%	15%	20%
Overhead and Fee	45%	50%	45%

TABLE 9. CPPP COST REDUCTIONS USED IN ANALYSES

	System 1	System 2	System 3
Process Planning	25%	40%	60%
Direct Labor	5%	7%	10%
Scrap and Rework	3%	6%	10%
Tooling	5%	7%	15%
Material	3%	3%	3%
Work in Process Inventory	2%	4%	4%

that software would be provided without cost. Hardware costs for terminals, printers and interfacing equipment were included. Costs for computer usage were based on charges for time used rather than the purchase of computer systems.

Thirty-six analyses were performed. For each type of manufacturer and for the composite of companies responding to the survey, benefits were calculated for each system and for cylindrical and noncylindrical parts. Each cylindrical analysis was performed for two rates of attaining benefits, the second usually more optimistic than the first. Table 10 gives the results of the original analyses. Results of the second set of analyses, performed for cylindrical parts, are shown in Table 11.

TABLE 10. SUMMARY OF CASH FLOW ANALYSIS RESULTS FOR TWENTY-FOUR ORIGINAL CASES

Manufacturer	Parts	System	Return on Investment	Net Present Value
Large Size (High Part Similarity)	Cyl	1	264%	$2484K
		2	193	3429
		3	127	4200
	Non-cyl	1	241	2700
		2	202	3862
		3	110	4837
Medium Size (Fair Part Similarity)	Cyl	1	105	388
		2	63	447
		3	38	427
	Non-cyl	1	109	375
		2	61	428
		3	29	345
Small Size (High Part Similarity)	Cyl	1	135	254
		2	62	315
		3	38	283
	Non-cyl	1	124	269
		2	59	336
		3	30	263
Composite	Cyl	1	196	1625
		2	123	2251
		3	101	3191
	Non-cyl	1	52	951
		2	120	1616
		3	103	2361

TABLE 11. SUMMARY OF CASH FLOW ANALYSIS RESULTS FOR THE TWELVE ADDITIONAL CASES. These analyses were performed for each cylindrical case using an alternative, usually more optimistic, rate of attaining benefits.

Manufacturer	System	Return on Investment	Net Present Value
Large Size (High Part Similarity)	1	317%	$2887K
	2	243	4008
	3	172	4927
Medium Size (Fair Part Similarity)	1	126	474
	2	78	576
	3	46	549
Small Size (High Part Similarity)	1	168	299
	2	77	380
	3	50	366
Composite	1	198	1698
	2	124	2354
	3	89	3001

Benefits are clearly greater when volume of business and part similarity are greater. The large manufacturer with high part similarity receives the largest benefits. This tends to verify the intuitive opinion that volume of business and part similarity are important economic factors. Pairwise comparison of the medium/similar and small/highly similar cases does not indicate which of these factors is more important. In some cases, the medium/similar company receives greater benefits. In others, the reverse is true. Results for the three scenarios are compared in Figure 48.

Comparison of the three systems yields mixed results. Return on investment generally decreases as system sophistication grows. On the other hand, the cumulative present value after ten years generally increases with system sophistication. System 1 yields the greatest return on investment in all situations, while System 3 provides the largest cumulative present value. Figure 49 illustrates these trends.

The more sophisticated systems require greater implementation costs but ultimately yield greater absolute savings. However, the incremental savings of the more sophisticated savings are smaller in proportion to the investment required. The fact that discounting places more weight on early

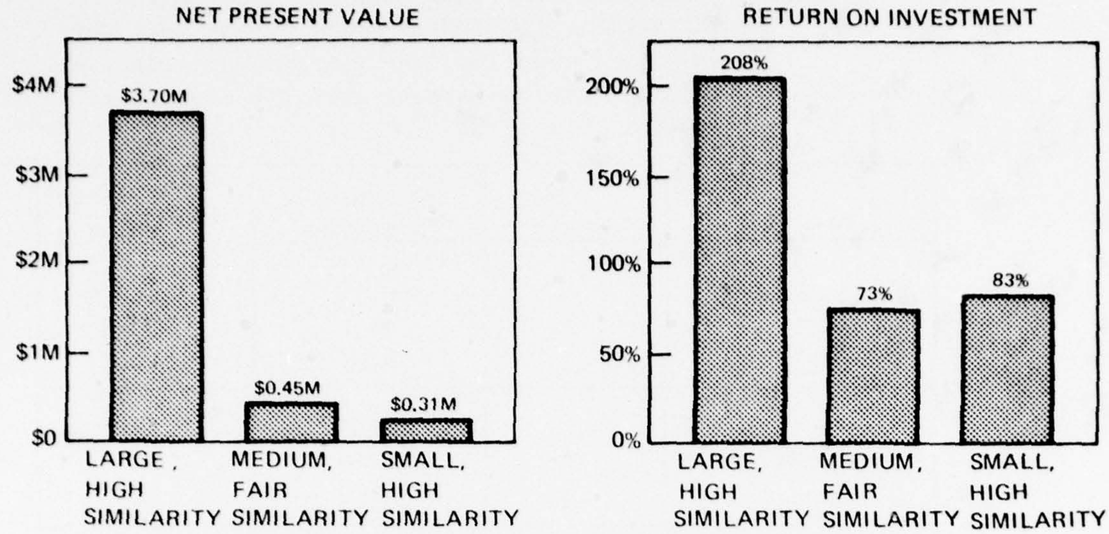

FIGURE 48. DEPENDENCE OF BENEFITS ON MACHINING VOLUME AND PART SIMILARITY. Each bar shows average results for the nine analyses performed for the manufacturing environment.

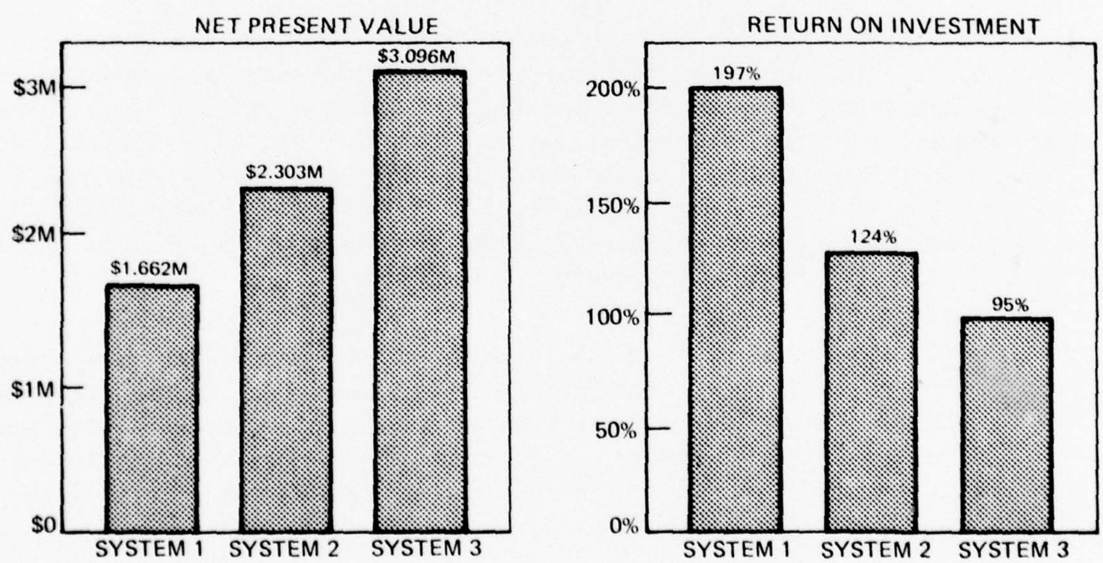

FIGURE 49. RESULTS OF CASH FLOW ANALYSES FOR COMPOSITE OF RESPONDING COMPANIES The graphs above are for cylindrical parts, using the average of the two analyses performed.

investment costs and less weight on later cost savings tends to favor the less sophisticated systems. These remarks lead to three further observations:

1. The estimated useful life of the systems is important. Calculations for each system assumed a ten-year life. The more sophisticated systems will yield greater savings over a longer time period.

2. The discount factor is important. A lower factor would tend to equalize investment costs and savings. The appeal of a more costly, more capable system would be greater under these circumstances.

3. When return on investment and present value conflict, external factors must be weighed. Capital availability, risk and the promise of other potential investments are critical.

The data and analyses reported above suggest that computer-aided process planning is economically promising. However, the reader is cautioned that the analyses were performed for generalized manufacturing situations, using data obtained by survey and the judgment of the Contractor. Expected benefits for any particular company must be determined as a function of that company's own operations and environment.

3.2 Case Study of CPPP Benefits[1]

Results of a study of CPPP benefits for the Hamilton Standard Division of United Technologies Corporation are presented below. Hamilton Standard has participated in the development of CPPP since 1974, acquiring an understanding of the system's capabilities and its potential savings and costs. The company is a sizable manufacturer of machined parts for aircraft systems such as fuel controls, environmental control systems, and actuator controls. Cylindrical parts account for approximately 40 percent of machining costs.

Estimates of costs and savings were made for two CPPP capabilities. The first is the basic CPPP system demonstrated under the present contract. The second is a more advanced system incorporating the improvements listed below. An analysis of the second system was done to show the benefits achievable through continued development of the technology.

1. Complete dimensioning and tolerancing of machined parts
2. Complete processing of noncylindrical features

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[1] The Hamilton Standard Division of United Technologies Corporation participated in the work reported in this section.

3. Selection of standard procedures
4. Selection of specific cutter tools
5. Calculation of standard times and costs
6. Selection of holding and inspection tools
7. Advanced machining analysis

Figure 50 shows the average cost breakdown for manufacturing machined parts. CPPP is estimated to have a direct cost reduction impact on three of the cost components shown: process planning, direct labor, and tooling. These components account for 43 percent of production cost.

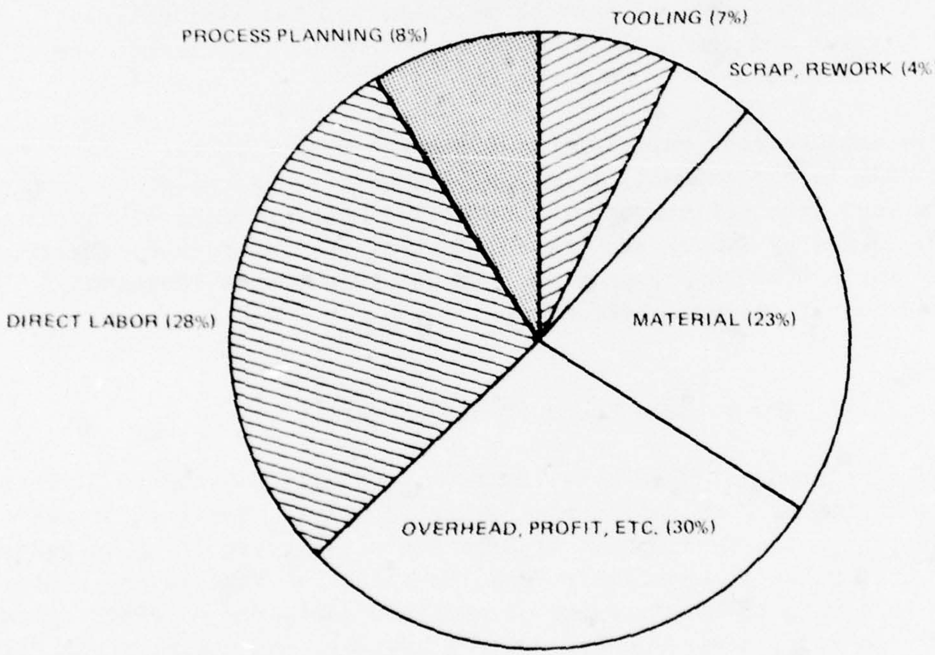

FIGURE 50. COST BREAKDOWN FOR MACHINED PART MANUFACTURING

Manual process planning for cylindrical parts sampled in the study required an average of 104 manhours. (This includes the setting of standard times and costs.) Figure 51 shows a breakout of this total by function. The impact of CPPP on each function was evaluated to yield the labor requirements given in Table 12. The basic CPPP capability is estimated to reduce labor for a new plan by 39 percent to 63.5 manhours. The labor requirement is estimated to be 21.5 hours using the advanced CPPP, a 79 percent saving. Figure 52 illustrates these totals.

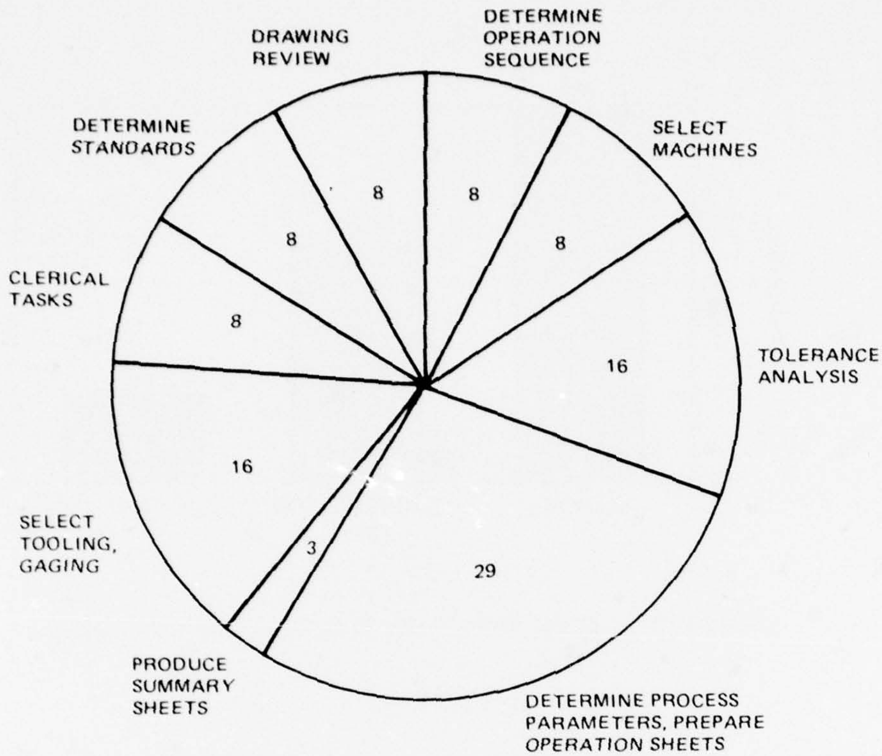

FIGURE 51. LABOR REQUIREMENTS FOR MANUAL PROCESS PLANNING. (Numbers show manhours.)

TABLE 12. CPPP IMPACT ON PROCESS PLANNING

Activity	Manual	Demonstration CPPP	Advanced CPPP
Drawing review	8 manhours	5 manhours	5 manhours
Determine operation sequence	8	1	1
Select machines	8	3	1
Tolerance analysis	16	10	4
Determine process parameters, prepare operation sheets	29	14	3
Produce summary sheets	3	0.5	0.5
Select tooling, gaging	16	14	3
Clerical tasks	8	8	2
Determine standards	8	8	2
Total	104 manhours	63.5 manhours	21.5 manhours
Reduction		39%	79%

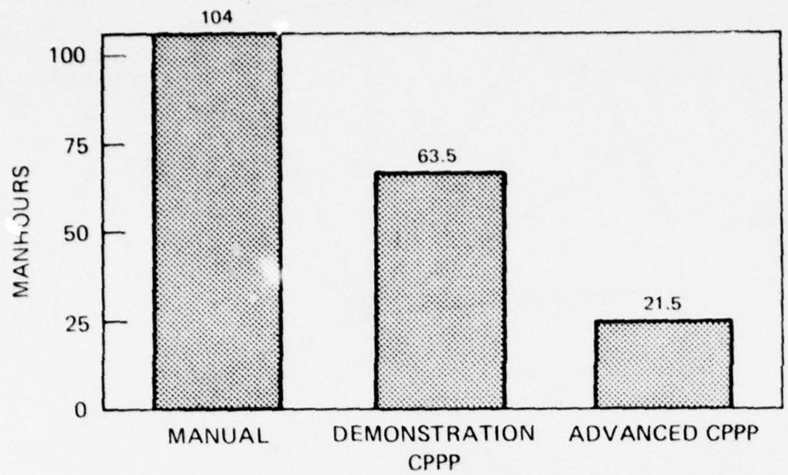

FIGURE 52. CPPP IMPACT ON PROCESS PLANNING LABOR

The process standardization resulting from use of CPPP is expected to yield significant reductions in machining costs. Operational experience with the system is needed before these savings can be quantified with confidence. It is currently estimated that a 2 percent to 7 percent reduction in machine operator labor will be obtained from the demonstration CPPP system.

The enhanced CPPP system offers additional savings in the shop. Optimization of the machining process is expected to increase operator savings to between 5 percent and 15 percent. The tool selection capability will yield savings due to standardization, and machining optimization will result in longer tool life. Savings from standarization and reduced cutter consumption are estimated at 3 percent to 10 percent of costs for cutting tools. Figure 53 illustrates CPPP savings in the shop.

Recurring costs for computer use, system maintenance, and data base maintenance will partially offset the savings discussed above. Average computer costs for a process plan are estimated at $105 for the demonstration CPPP and $155 for the advanced system. Maintenance of CPPP programming and the large data base will require programmer/analyst labor, process engineer labor, and computer usage. Table 13 shows the expected level of effort. It should be emphasized that those figures do not include the substantial effort required to install CPPP and build the necessary data base.

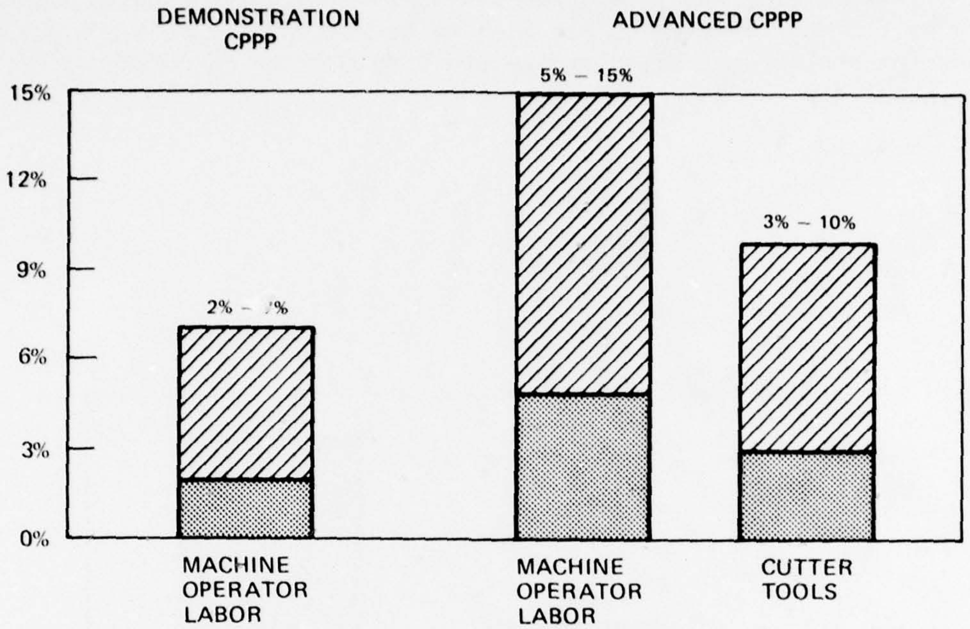

FIGURE 53. ESTIMATED CPPP SAVINGS IN SHOP FABRICATION
Estimates were expressed as ranges. Dark shading represents the lower end of the range; light shading, the upper.

TABLE 13. ESTIMATED ANNUAL EFFORT FOR CPPP MAINTENANCE.

	Demonstration CPPP	Advanced CPPP
System Engineers	1/3 manyear	1 manyear
Process Engineers	1/4 manyear	1 1/2 manyear
Computer Use	$3,000	$6,000

The recurring costs and savings presented above were reduced to dollars using 1977 rates and volume of business. Net annual recurring savings, which do not include implementation costs, were calculated using the mean of the range for shop savings. This yielded an estimate of $145,000 yearly savings for the demonstration system and $350,000 for the advanced CPPP (Figure 54).

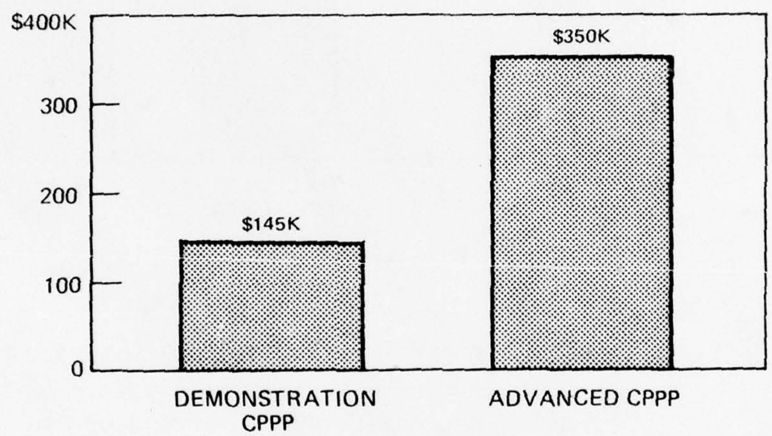

FIGURE 54. ESTIMATES OF NET ANNUAL RECURRING SAVINGS FROM CPPP. These savings were calculated using the means of the ranges estimated for shop cost reductions.

A manufacturer implementing CPPP will incur significant costs in installing the system and, especially, in developing the necessary data base. Some training of personnel will be required. Terminals will probably be purchased. Table 14 gives estimates of the implementation effort. For both the demonstration and enhanced systems, the implementation cost is slightly greater than a single year's estimated savings as shown in Figure 54.

TABLE 14. CPPP IMPLEMENTATION COST ESTIMATES.

	Demonstration CPPP	Enhanced CPPP
Process Engineers	3-3/4 manyears	9-1/2 manyears
System Engineers	1/2 manyear	3 manyears
Computer Use	\$7,000	\$28,000
Terminals	\$15,000	\$15,000

3.3 Defense Industry and Government Agency Benefits[1]

A three-step estimation of CPPP benefits to defense industry and Government agencies is reported below. First, industry opinion on the potential economic impact of the system was surveyed. Next, an analysis of CPPP impact on defense industry was developed. This took the form of cash flow analyses for three hypothetical manufacturers of cylindrical parts. Finally, the results of the defense industry analysis were used to project savings in three procurement areas -- Army missiles, total Army equipment, and Department of Defense equipment.

3.3.1 Survey and Response

The survey was mailed to 150 companies. The mailing list consisted of defense suppliers who received the general industry survey plus additional companies named by the Missile Command. The survey described the capabilities of CPPP and requested data on manufacturing costs for machined cylindrical parts. Estimates of the impact of CPPP on fabrication of cylindrical parts were solicited: cost savings, intangible benefits, local implementation costs and recurring costs. (The survey is shown in Appendix H.)

Thirteen companies responded to the survey (Table 15). Five indicated they supply products for Army missiles and rockets, three are suppliers of other Army equipment and all thirteen manufacture products for other Department of Defense agencies.

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[1]The work reported in this section was largely performed by the IIT Research Institute.

TABLE 15. COMPANIES RESPONDING TO DEFENSE INDUSTRY SURVEY

Avco-Lycoming
General Dynamics, Pomona Div.
Grumman Aerospace
Lockheed California
Lockheed Georgia
Lockheed Missiles and Space
McDonnell Douglas Astronautics
Rockwell International
Rockwell International, B-1
Systron Donner
United Technologies, Chemical Systems Div.
United Technologies, Sikorsky Aircraft
Westinghouse

The annual value of machined cylindrical parts produced by these companies averaged over $5 million. Process planning costs for cylindrical parts averaged $168,000 per year. Three of the companies use some form of computer aid in process planning.

The survey requested anticipated savings, implementation costs and maintenance costs of CPPP for the addressees' manufacturing operations. Table 16 gives average responses. The average reduction in overall manufacturing costs (including process planning) was estimated at 9.4 percent. Process planning cost savings were estimated to be 37.5 percent. Based on the average manufacturing and process planning costs reported by the surveyed companies, the estimated cost reductions from CPPP would yield savings of $488,000 in manufacturing costs, including $63,000 in process planning. Annual recurring costs were estimated at $50,000, offsetting the annual

TABLE 16. AVERAGE SAVINGS AND COSTS ESTIMATES FROM DEFENSE INDUSTRY SURVEY

Annual Savings - -	Overall	9.4% = $488,000
	(Process Planning)	(37.5% = $ 63,000)
Annual Maintenance Costs		$ 50,000
Installation Costs --	Hardware	$116,000
	Data Base and Training	$162,000

savings by approximately 10 percent. Installation of CPPP was estimated to require 10.4 months and $162,000. This effort includes system installation and testing, initial data base construction, and training of personnel. An average of $116,000 worth of new computer hardware was felt to be needed. Responses to this question varied radically. Some respondents apparently felt they would need larger computer installations to use the system.

In order to identify specific benefits, the survey listed several areas in which CPPP was felt to have a potential impact. Addressees were asked to check those items for which CPPP offers a major positive advantage. Table 17 shows responses. The majority of the companies felt that CPPP offers major benefits in manufacturing costs, production lead time, production scheduling, process plan uniformity, and cost estimation. Almost half felt that machine and direct labor utilization would improve significantly. (The Contractor feels there will be major advantages in these two areas.)

Each company was also asked to identify possible obstacles to CPPP implementation. Economic justification and the establishment of initial data bases were most often cited. Management commitment and three items pertaining to the needed technical effort (interfacing with existing systems, testing and debugging, system complexity and reliability) were checked by about half of the respondents.

3.3.2 Benefits to Defense Industry

Cost benefit analyses were performed using the cash flow model described in 3.1.3. The three manufacturing environments defined in 3.1.3 were analyzed for two CPPP capabilities. The first is the demonstration CPPP. The second is the advanced version described in 4.0. Inputs to the model (installation costs, recurring cost, savings factors, process plan turnover rate, etc.) were estimated by the Contractor. Responses to the defense industry survey plus the Contractor's judgment were the primary determinants of input values. (It should be noted that the CPPP system described in the survey is an intermediate capability, more advanced than the demonstration CPPP but less capable than the enhanced system.) A complete listing of inputs for each analysis is given in Appendix H. Table 18 shows the cost reduction factors used for the major cost areas treated. These are the ultimate savings achieved after CPPP is fully operational.

The cash flow analyses yielded good economic performance in every case. Figures 55 and 56 show results in terms of benefit-to-cost ratios and net present value. Evaluation of results with respect to manufacturing environment and system sophistication leads to the same conclusions reached in the general industry analysis. Benefits are greater as manufacturing volume and part similarity increase. The analysis does not show which of these two factors is more important. The more capable system yields greater dollar savings. The smaller investment required for the less capable system results in quicker payback and higher benefits-to-cost ratio.

TABLE 17. RESPONSES TO THE QUESTION: WILL CPPP HAVE MAJOR ADVANTAGES IN THIS AREA?

Area	"Yes" Responses
More Uniform Process Plans	92%
Reduced Production Leadtime	77%
Reduced Manufacturing Costs	69%
Improved Production Scheduling	62%
Improved Cost Estimating Procedures	54%
Increased Machine Utilization	46%
Increased Direct Labor Utilization	46%
Improved Capacity Planning	46%
Reduced Critical Labor Skills	38%
Improved Product Quality	38%
Better Make/Buy Decisions	23%
Increased Product Standardization	23%
Improved Producibility of Parts	23%
Better Material Handling	23%
Better Plant Layout	15%
Improved Raw Material Standardization	8%

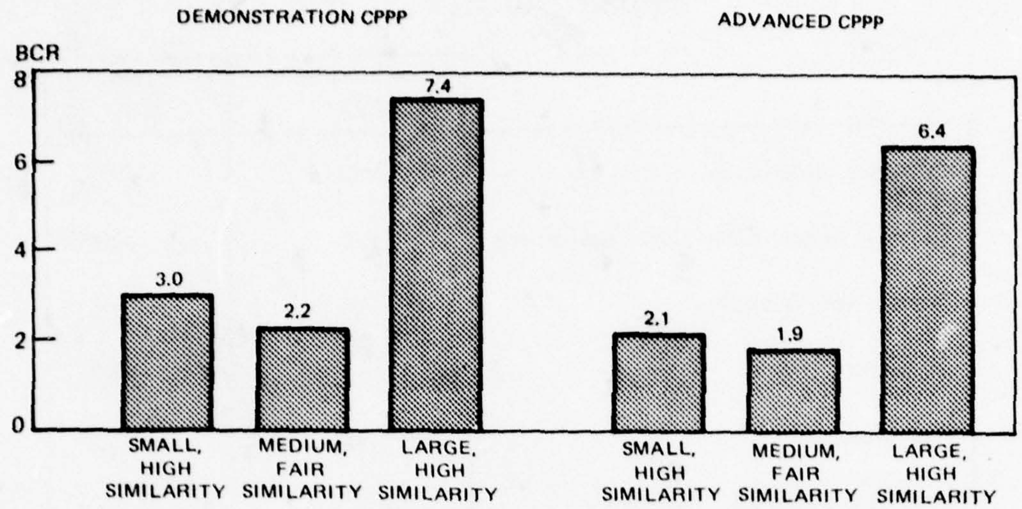

FIGURE 55. ESTIMATED CPPP BENEFIT-TO-COST RATIOS FOR DEFENSE COMPANIES FOR A TEN YEAR PERIOD.

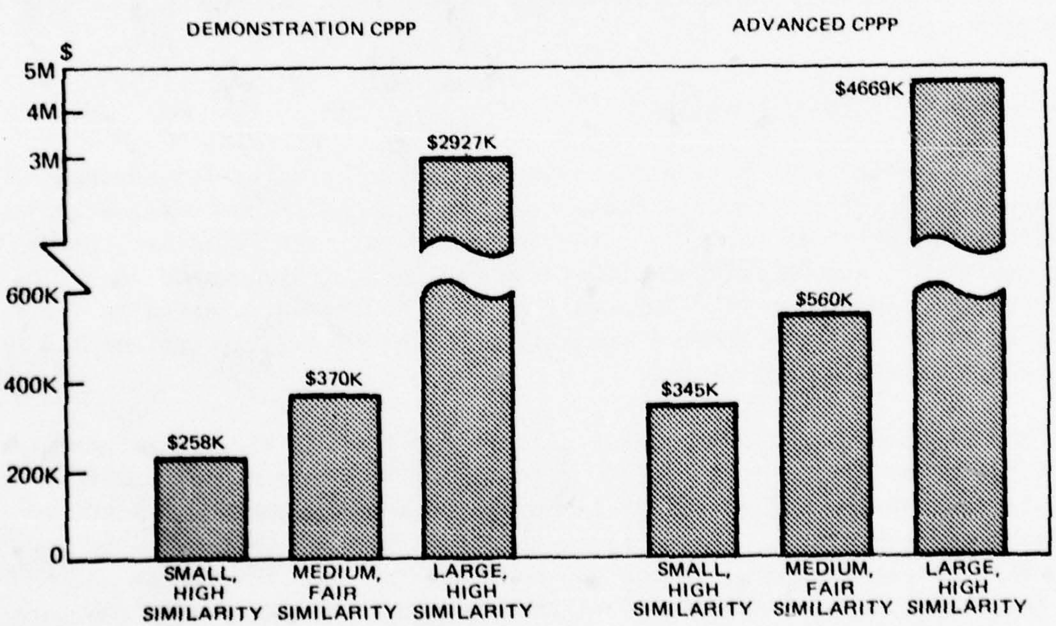

FIGURE 56. ESTIMATED DISCOUNTED CUMULATIVE NET PRESENT VALUE OF CPPP TO DEFENSE COMPANIES FOR A TEN YEAR PERIOD.

TABLE 18. COST REDUCTION FACTORS USED IN DEFENSE INDUSTRY CASH FLOW ANALYSES

	Demonstration CPPP	Advanced CPPP
Process Planning	40%	80%
Direct Labor (Machine Operators)	5%	10%
Scrap and Rework	6%	10%
Tooling	5%	15%
Material	3%	3%
Work in Process Inventory	4%	4%

It should be noted that the analysis above is subject to the same uncertainties mentioned in 3.1. It is performed for "typical" manufacturing situations and based on the judgment of companies responding to the survey and the Contractor. Estimation of benefits to any particular defense supplier requires careful consideration of CPPP's capabilities in relation to that company's operations.

3.3.3 Defense Agency Benefits

CPPP benefits were projected to defense agencies using the assumption that defense suppliers' savings and costs are passed along to procuring agencies. Benefits were estimated in three procurement areas: Army missiles, overall Army equipment, and Department of Defense equipment. Discounted cash flow analyses for the period FY78 through FY87 were performed. Inputs to the analyses were drawn from the defense industry analyses of 3.3.2, supplemented by necessary contractor estimates.

Three analyses, offering three different points of view, were performed. The first shows CPPP's full savings potential. Procurement savings were calculated assuming use of the system by all defense suppliers. A second analysis was performed, using a realistic projection of CPPP usage by industry. In both of these analyses, it was assumed that the full investment was made (by individual defense suppliers) at the start of the time period and that full benefits were realized immediately. This is a common tactic for avoiding problematical estimates of investment and benefit phasing. These issues were addressed in the third analysis. An industry implementation schedule was estimated and used in the cash flow analysis.

The CPPP system is currently applicable only to machined cylindrical parts. It was, therefore, necessary to estimate procurement costs for these parts. These were estimated as the product of two factors: (1) total procurement budget and (2) the percentage attributable to machined cylindrical parts.

To estimate total procurement costs, actual and projected procurement budgets published by the Office of Management and Budget were obtained. After considering the trends of the 1974 through 1978 budgets, it was decided that an annual increase of approximately 10 percent could be expected. Hence, procurement costs for 1979 through 1987 were estimated using 1978 as a base year and a 10 percent increase factor. The 1978 base estimates were $657 million for Army missiles, $6.342 billion for all Army equipment, and $35.143 billion for Department of Defense equipment.

Very few data were available on the portion of procurement costs attributable to machined cylindrical parts. In the general industry survey discussed in Section 3.1, companies were asked to estimate the value of machined cylindrical parts as a fraction of total product value. The average response for missile contractors was 12.1 percent. In a case study presented at the Missile Manufacturing Technology Conference in 1975, machined parts (including non-cylindrical) accounted for 14 percent of the standard hours for production of a missile.[1] From this evidence, it was estimated that machined cylindrical parts represent 10 percent of Army missile procurement costs. Cylindrical component costs for overall Army and Department of Defense procurement were extrapolated from the estimate for missiles. Machined cylindrical parts are clearly a smaller portion of costs in many major procurement areas of these agencies -- ammunition, weapons, tracked vehicles, ships, etc. Hence, it was estimated that 5 percent of Army and Department of Defense procurement is attributable to cylindrical parts.

The investment required of defense suppliers implementing CPPP and the resulting benefits were derived from the analyses for "model" defense manufacturers. For the demonstration CPPP, implementation costs for the three companies averaged 1.30% of annual costs for cylindrical part fabrication. The corresponding figure for the advanced system was 2.99%. Net savings, with full system utilization, were 3.15% for the demonstration CPPP and 5.45% for the advanced capability.

Cash flow analyses were performed using the parameters above and assuming use of CPPP by all defense manufacturers. The results, shown in Table 19, give an estimate of CPPP's potential to reduce procurement costs.

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[1] Peterson, R.S.: An Approach to Long Range Cost Effectiveness, Proceedings of the U.S. Army Material Command Missile Manufacturing Conference, 1975.

TABLE 19. PROCUREMENT COST SAVINGS POTENTIAL OF CPPP. These savings estimates were calculated for FY78 through FY87, assuming full use of CPPP by defense suppliers.

	Demonstration CPPP		Advanced CPPP	
Agency	Undiscounted ($ Millions)	Discounted ($ Millions)	Undiscounted ($ Millions)	Discounted ($ Millions)
Army (Missiles)	32.129	18.878	55.102	32.176
Army	155.071	91.116	265.949	155.296
Department of Defense	859.297	504.901	1473.703	860.541

The same method was used for a second analysis, except that a projection of CPPP use by defense industry was factored into the calculations. Such an estimate is, of course, highly judgmental. The survey response shows a favorable opinion of the system's savings potential. There are, however, many obstacles to widespread adoption of a single system. The willingness of suitable organizations to commercialize the system (i.e., make it publicly available and provide marketing and user support), future enhancements funded by industry or government, and the success of alternative systems are important factors. Use of the system by 15% of defense industry was felt to be a reasonable estimate. Use of this factor resulted in the savings estimates of Table 20.

TABLE 20. ESTIMATED PROCUREMENT COST SAVINGS FROM CPPP. These savings were calculated for FY78 through FY87, assuming that 15% of defense industry uses the system.

	Demonstration CPPP		Advanced CPPP	
Agency	Undiscounted ($ Millions)	Discounted ($ Millions)	Undiscounted ($ Millions)	Discounted ($ Millions)
Army (Missiles)	4.819	2.832	8.265	4.826
Army	23.261	13.668	39.892	23.295
Department of Defense	128.895	75.736	221.055	129.081

In the third analysis of defense procurement benefits, time-phased realization of savings was considered. There are two time factors that affect the achievement of procurement savings. First, adoption of the CPPP system by defense industry would occur over a period of time. Second, cost reductions obtained by an individual defense supplier are dependent on the amount of time elapsed since that company started implementation. These two factors were quantified by projecting a schedule of CPPP adoption by industry and by deriving time-dependent company savings factors from the analysis of 3.3.2.

Estimation of an industry implementation schedule was, of course, highly judgmental. It was felt that (1) implementation before FY79 is unlikely, (2) ultimate use of CPPP by about 15 percent of defense machining industry is a reasonable projection, and (3) implementation will occur, at an increasing rate, over several years. This rationale yielded the schedule shown in Table 21.

TABLE 21. PROJECTED DEFENSE INDUSTRY IMPLEMENTATION OF CPPP. Figures show industry using CPPP as a percentage, by dollar value, of machined cylindrical part procurement.

Fiscal Year	New Implementation	Cumulative Implementation
1979	1%	1%
1980	1%	2%
1981	3%	5%
1982	5%	10%
1983	5%	15%

The industry analysis described in 3.3.2 and Tables H1 - H18 was used to quantify CPPP impact on company costs as a function of time. For the demonstration and the advanced CPPP capabilities, a cost impact factor was derived for each year after start of implementation. This factor is the average, for the three model companies considered in 3.3.2, of the before taxes impact on the companies' costs for that year. For example, in the fifth year after start of implementation, before taxes savings due to the demonstration CPPP were $1,186,000, $225,000, and $123,000 for the three model companies (Tables H2, H5, and H8). These are 2.37 percent, 2.25 percent and 2.46 percent of total costs. Hence, a reduction factor of 2.36 percent was estimated in the cost of parts procured from companies in the fifth year after implementing the demonstration CPPP system. Table 22 shows the factors derived in this manner.

TABLE 22. PROJECTED CHANGE IN COST OF PROCUREMENT FOR A COMPANY USING CPPP. Cost reductions/increases are shown as a function of time since start of implementation. Positive numbers indicate increased costs; negative, reduced.

Year	Demonstration CPPP	Advanced CPPP
1	+ .79%	+ 1.05%
2	+ .50%	+ 1.69%
3	- .56%	+ .24%
4	-1.26%	- 1.65%
5	-2.36%	- 3.64%
6	-3.15%	- 4.94%
7,8, etc.	-3.15%	- 5.45%

The implementation schedule of Table 21 and the time-dependent cost change factors of Table 22 were used to project procurement savings for FY79 through FY87. Savings for each year were calculated by the formula

$$S = C*\left(\sum_{N} P_N F_N\right)$$

where

S = savings in cylindrical part procurement in a procurement area (Army missiles, overall Army equipment, or Department of Defense equipment)

C = estimated cost (before CPPP impact) of cylindrical part procurement

N = number of years since start of CPPP implementation

P_N = the portion of industry in the N^{th} year of using CPPP (Table 21)

F_N = the cost change factor for industry in the N^{th} year of using CPPP (Table 22)

Table 23 shows total savings for the period for each CPPP capability and procurement area. Tables H19 - H24 give details of each analysis.

TABLE 23. PROJECTED SAVINGS IN DEFENSE PROCUREMENT USING ESTIMATED SCHEDULE FOR CPPP IMPLEMENTATION BY INDUSTRY. These savings for the period FY78 - FY87 were calculated using the industry implementation schedule of Table 21 and the phased cost changes of Table 22.

	Demonstration CPPP		Advanced CPP	
Agency	Undiscounted ($ Million)	Discounted ($ Million)	Undiscounted ($ Million)	Discounted ($ Million)
Army (Missiles)	1.463	.627	1.974	.801
Army	7.065	3.027	9.526	3.863
Department of Defense	39.147	16.773	52.785	21.404

There is a striking difference between the results in Table 20 and those in Table 23. This is primarily due to the short period of system usefulness implicit in the latter analysis. In that analysis, the average period of CPPP implementation and use is only six years. In the first two or three of these years, implementation costs exceed savings. Hence, there are only three or four years during which savings are obtained. In the analysis of Table 20, full savings were obtained during the entire ten-year period.

In the Contractor's opinion, the useful life of CPPP (or equally capable systems) will extend well beyond the 1980's. Major manufacturing systems which apply state-of-the-art technology are not replaced every few years by the typical company. Instead, they are incrementally improved as additional technology is proven useful. Furthermore, the replacement of multi-user systems occurs gradually, as did their adoption. It is therefore felt that, with effective support, the benefits of CPPP in defense procurement would continue well after the 1987 limit in the analysis of Table 23.

The analysis above cannot be considered conclusive. Little evidence was available for estimating several of the factors used in the calculations -- procurement budgets, the fractions of budgets attributable to cylindrical parts, the implementation of CPPP by defense industry, and the expected period of system usefulness. Furthermore, the calculations are dependent on the defense industry benefit analysis, whose uncertainties have already been mentioned.

Despite its uncertain quality, the analysis suggests that CPPP has a large cost reduction potential in defense procurement. Savings of several millions per year are projected after full implementation is achieved. Greater industry acceptance would increase savings. Government activities which would enhance CPPP capabilities and/or reduce implementation effort could increase acceptance as well as increasing the savings realized by companies using the system.

4.0 RECOMMENDED CPPP ENHANCEMENTS

The demonstration CPPP system is viewed as only the first phase of an advanced computerized process planning technology. Several years will be required before CPPP fully matures. The present system was developed with evolution in mind. It is highly modular and provides the overall framework to plan production methods for machined parts. To date, the main effort has been to fully understand the variables of process planning and to develop an approach that systematically incorporates all aspects of the planning process. The result has been the development of a base system into which scientific principles of metalworking and workshop practice are easily introduced. The following list of enhancements is offered to guide future program planning:

1. Process decision modeling should continue to be developed. A method of implementing manufacturing rationale in the computer is necessary for computerized process planning. The modeling technique can be advanced to provide full generative planning for cylindrical and non-cylindrical parts.

2. Development of advanced methods of geometric modeling is needed to plan production methods for non-cylindrical parts and features. Parts must be modeled as solid objects and their data structure must convey all physical attributes of the design.

3. Methods of dimensioning machined parts should continue to be developed. This includes the capability to analyze tolerance buildup and the impact of tolerance on processing for all design configurations. Special process effects and the choice of datum surfaces should also be included in the method of analysis.

4. Cutter tool selection analysis should be developed. This will allow for selecting qualified cutter tools from a data base of tools. CPPP currently selects only tools preassigned to a machine tool for a specific type of cut. The enhancement would analyze variables of the cutting situation and determine which tools should be considered.

5. A method of calculating standard times and costs should be developed. This will allow the use of standards data in CPPP production rate and cost calculations. CPPP now requires the manufacturer to estimate variables such as piece handling, machine setup, tool change, operator time, etc.

6. Machining analysis methods should continue to be developed. This includes a detail stock removal analysis and mathematical methods of determining combinations of feed, speed, and depth in single and multiple pass cutting situations.

7. Methods of selecting holding tools and inspection tools are needed. This will provide for the selection of fixtures and gages from a data base of tooling based on characteristics of the workpiece and machine cuts.

APPENDIX A

STRUCTURED DECOMPOSITION OF CPPP

This Appendix contains a top-down decomposition of the CPPP system. Figure A1 illustrates the technique of factoring general system functions into greater levels of detail. In the example, the most general view of CPPP is the box A0 -- "DC Computer Process Planning." This view is also represented by a diagram in which five boxes are interconnected -- this is the first level of structured decomposition. Each box represents a high-level system function and the connected paths carry data between functions. Therefore, at any level of viewing the CPPP system, the data interfaces are defined. The process of factoring functions can continue to any level of detail desired. In the example, two of the A0 functions are further factored and one of these -- "Generate Operation Plans" -- has a function factored once again.

This method of decomposition has been called "cell modeling" and more recently "structured analysis and design". It results in a documentation that is somewhat a blueprint of the system. The diagrams identify the input/output data interfaces between functions of the same or higher levels and show the decomposition of a function into its subfunctions. Although there is a convention used in diagraming, the diagrams can be read with understanding without a full explanation of the conventions. For the diagrams presented here, it is only necessary to know that connecting paths pointing into a box carry input or control data and that paths coming out of a box carry output data. Also, paths that do not connect with a box of a diagram carry data from or to functions of the next higher level diagram.

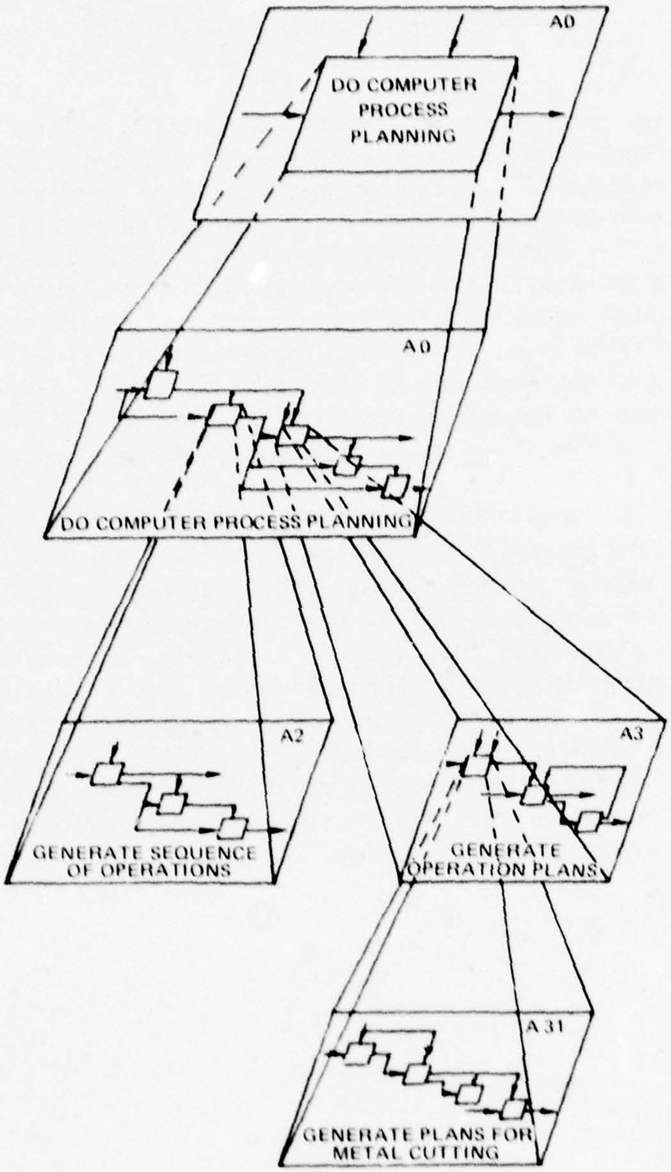
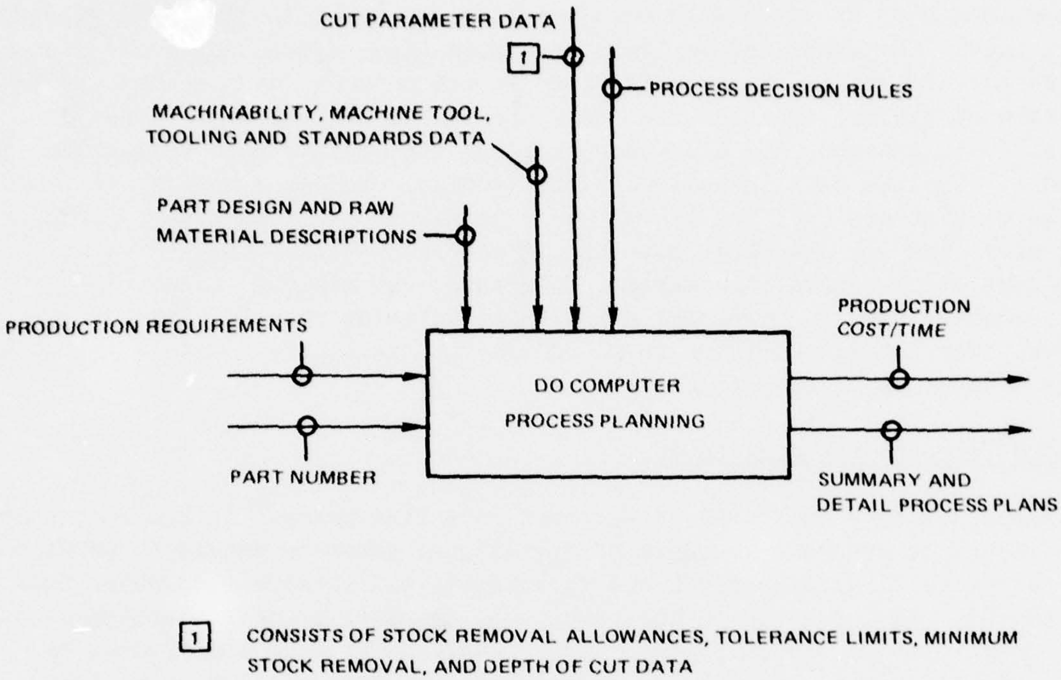


Figure A1. STRUCTURED DECOMPOSITION

DO Computer Process Planning (Context)



This diagram shows computer process planning in the context of the data needed to perform that function -- which is, the generation of summary and detailed process plans from input of part design and raw material (workpiece) descriptions. The data describing the part design must contain the equivalent information content of a blueprint for all part surfaces and features. It must include dimensional data, tolerances, form conditions (concentricity, straightness, perpendicularity, flatness), radii and edge breaks, finish, heat treatment, coding and plating requirements, feature specifications (windows, radial and bolt holes, flats, keyways, slots, threads), and the type of material and its hardness. Input describing the workpiece must specify dimensions of the raw material, which can be in the form of bar stock, extrusions, forgings or castings. The finished part dimensions must be located relative to the raw material envelope so that the system will know how much stock must be removed from each surface.

The generation of a process plan also requires data about production requirements and the workshop. The production requirements must be input each time a plan is to be generated. It specifies the lot size and indicates

whether the criterion for generating the process plan is optimum production rate or cost. The machinability, machine tool, tooling, standards, and cut parameter data must be defined by manufacturing and input to the system through the data base. The machinability data specifies feed, speed, depth of cut, and tool life for different cutting situations -- the data is input to the system in the form of tables. Machine tool data provides description of lathes, grinders, drill presses, and all other machines that can be used in fabricating a part. Tooling data identifies cutter tools. Standards data are estimates of time and cost for setup, piece handling, tool changing, gaging, etc. The cut parameter data is defined in note 1 of the diagram; the stock removal allowances, tolerance, and minimum stock removal data are used to determine dimensions and tolerances in each operation. The process decision rules provide the rationale to generate a sequence of operations.

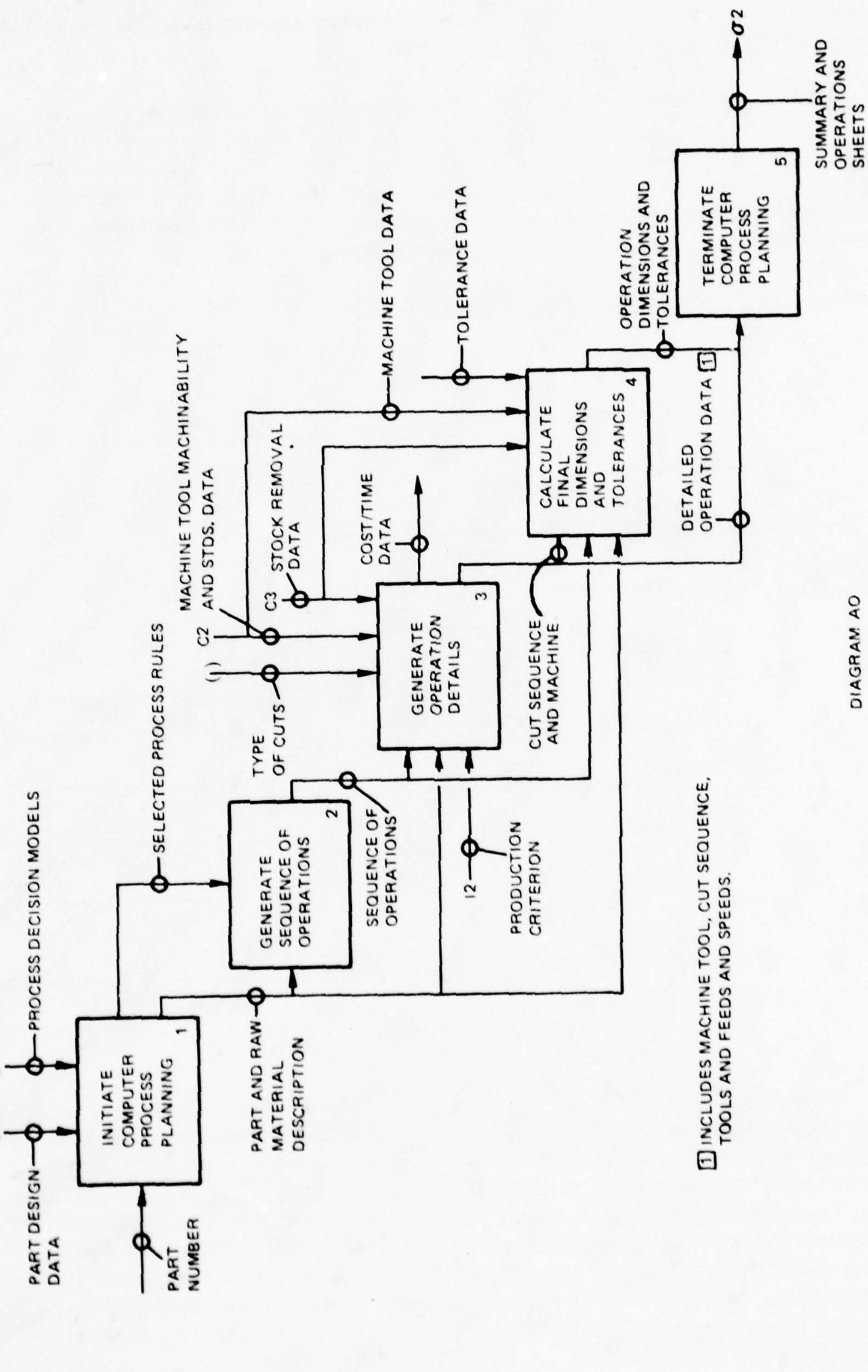
DO Computer Process Planning (AO)

Diagram AO shows that CPPP is factored into five parts: initiate computer process planning; generate sequence of operations; generate detailed operation plans; determine final dimensions and tolerances; and terminate computer process planning. As indicated in the first box, computer process planning is initiated by input of a part number. The primary outputs of the system, as shown in the fifth box, are the summary and operation sheets for fabricating the part.

The initiate CPPP function requires the process planner to input the part number along with other startup data identifying the process planner's name, lot size, production criterion, planner interaction control options, and mode of operation. Once the startup data is input, CPPP will retrieve from the data base the part design and workpiece descriptions and the associated part family process decision rules.

The first planning function (second box) will generate a sequence of operations. This is done under control of either the selected process decision rules or through interaction with the process planner. In the latter case, the process planner would specify the operations (metalcutting and non-metalcutting) and the surfaces to be cut in each metal removal operation.

The next planning function (third box) will generate detailed plans for each metalcutting and nonmetalcutting operation identified in the sequence of operations. This function requires data about the finished part, sequence of operations, and production requirements. Acting on this information, the function will select the best machines, cutting sequences, cutter tools, and machining parameters (feed, speed, depth of cut) for all metalcutting operations based on production time or cost. Also, as in the function to generate



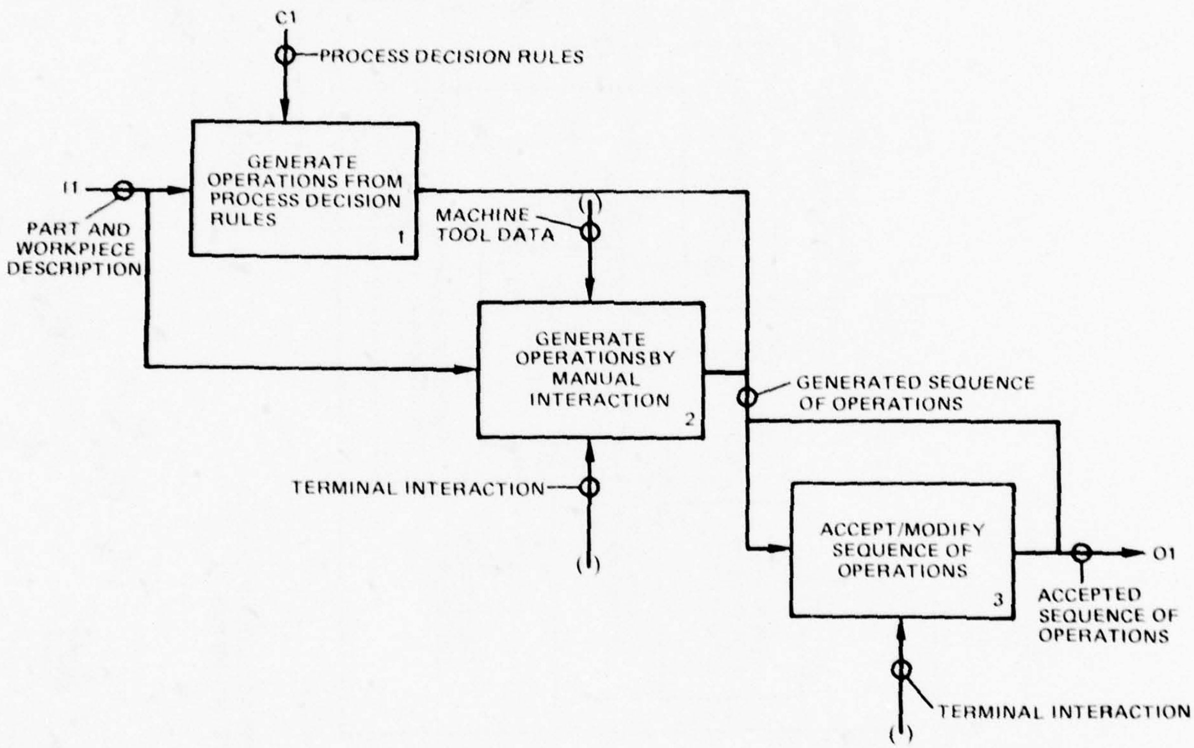
$\boxed{1}$ INCLUDES MACHINE TOOL, CUT SEQUENCE, TOOLS AND FEEDS AND SPEEDS.

DIAGRAM AO

a sequence of operations, the process planner may interact to exercise control over the detailed planning of operations.

The last planning function (fourth box) determines the final workpiece dimensions and tolerances. Up to this point, the system uses only nominal dimensions in generating detailed process plans. This function is a basic tolerance charting process consisting of diametral and lateral cut layout, distribution of tolerances over different types of cuts, and calculation of dimensions based on stock removal allowances.

<u>Generate Sequence of Operations (A2)</u>



This diagram shows that the function to generate a sequence of operation is factored into three parts: generate operations from process decision rules; generate operations from manual interaction; and accept/modify sequence of operations. An important operational feature is indicated by this diagram -- that is, operations can be generated by either automatic or man-machine interaction methods. The process planner indicates which method of operation is to be used at the time of system initialization. When operating in the interactive mode (box 2), the process planner defines to the computer each operation of the sequence. This would be done by specifying the type of operations, machine tools, and surfaces to be cut in each operation.

The first box of the diagram shows that the operations generated automatically are done so under control of process decision rules and input describing the part design and workpiece.

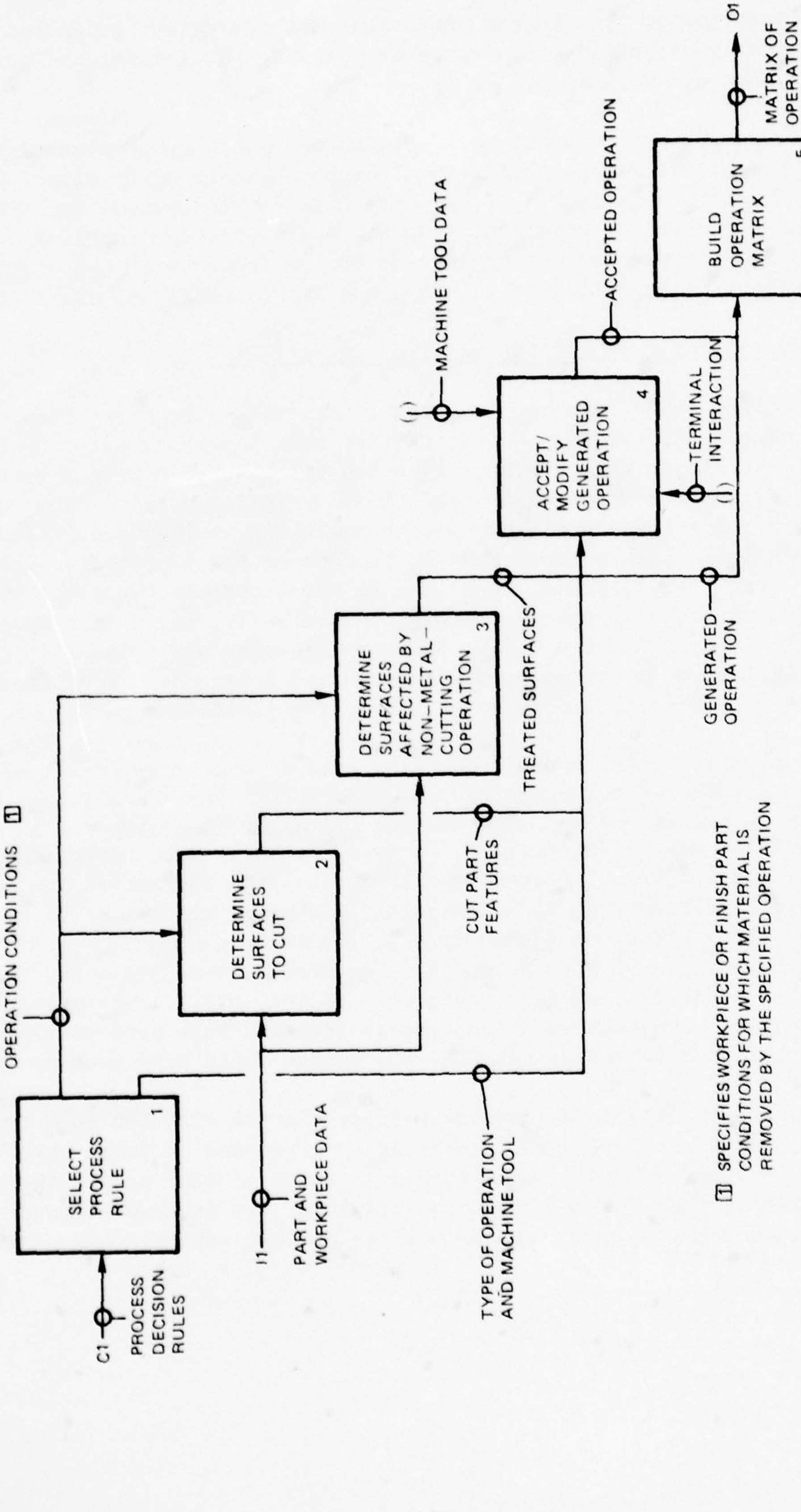
The third box provides the process planner with the opportunity to accept or modify a sequence of operations that has been generated by either the automatic or interactive methods. If the option is not requested, the system will automatically accept the sequence of operations. When the function is activated, the process planner can review the entire sequence of operations and make any additions or deletions to the sequence or individual operations.

Generate Operations From Process Decision Rules (A21)

Diagram A21 shows that the function to generate operations from process decision rules is factored into five parts: select process rules; determine surfaces to cut; determine surfaces affected by nonmetalcutting operation; accept/modify generated operation; and build operation matrix. The first function selects the process decision rule to determine whether conditions exist for an operation. Each process rule is programmed for a specific type of operation (turn, drill, grind, hone) and to use a certain class(es) of machine tool (engine lathe, automatic, numerical control, VTL, etc.) or a specific machine tool (W & S 2AB, J & L PFM, Van Norman centerless grinder). CPPP considers each process decision rule in turn and determines if an operation of the type specified should be selected for the particular part.

Associated with each process decision rule is a programmed set of conditions for which the stated operation is applicable. These conditions are interpreted in the second box to determine which part surfaces are to be cut and in the third box to determine surfaces affected by some nonmetalcutting operation. The conditions program the system to test the part for a specific shape, size, configuration, form, material, workpiece status, etc. If the set of conditions are present, the type of operation identified in the process decision rule will be selected. Conversely, when a process decision rule fails to identify a surface to be cut, plated, etc., the operation will not be selected. For example, if a process decision rule were programmed to cut a deep hole and there was not one, the system would skip such an operation.

The fourth function provides the process planner with the opportunity to accept or modify an operation generated by a process decision rule. If the option is not requested, the system will automatically accept the generated operation. When this function is activated, the process planner can add or delete cuts from the operation as well as perform several other actions.

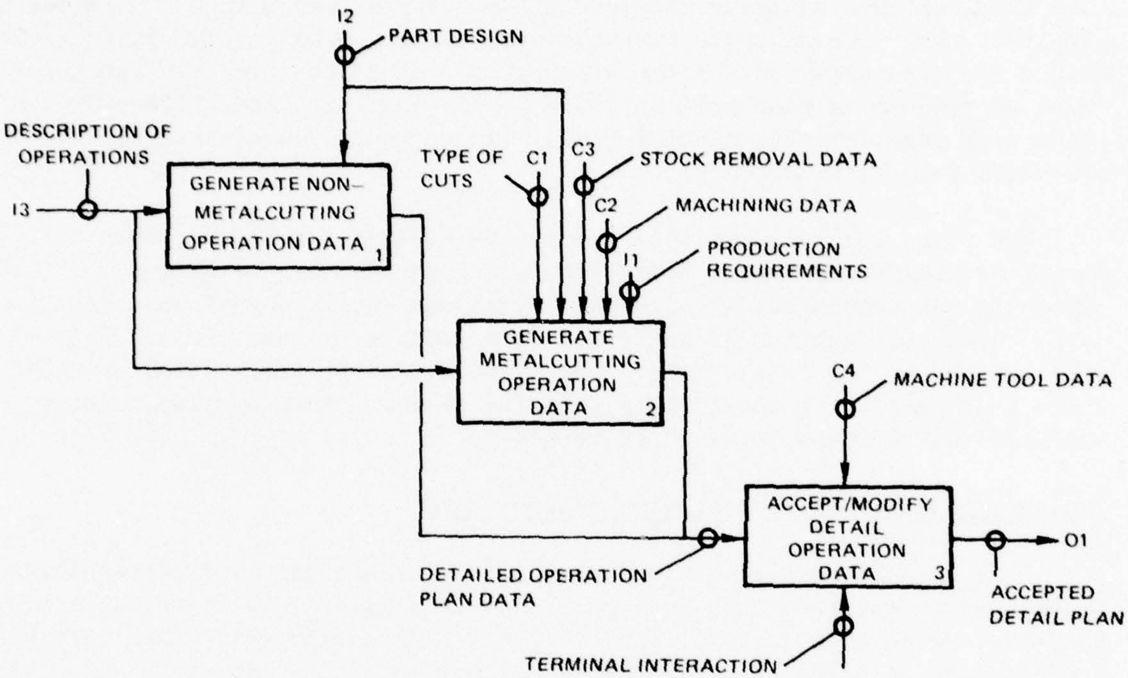


1 SPECIFIES WORKPIECE OR FINISH PART CONDITIONS FOR WHICH MATERIAL IS REMOVED BY THE SPECIFIED OPERATION

DIAGRAM A21

The final function builds the sequence of operations summary. The summary identifies for each operation the type of operation, machine class or specific machine, and the surfaces affected by the operation. A full sequence of operations is generated by cycling through all process decision rules programmed for the particular part family.

Generate Operation Details (A3)



This diagram shows that the function to generate detailed operation plans is factored into three parts: generate data for nonmetalcutting and metalcutting operations, and accept/modify detail operation data. The input to this part of the system is a sequence of operations summary fully describing each operation -- the type of operation (turn, drill, bore, crush grind, mill, plate) and either the type of machine tool or specific machine tool required. Also identified are the surfaces affected by each operation.

Depending on the type of operation, the first or second function is activated to generate the detail operation data. Detailed data generated for nonmetalcutting operations consist of a dimensioned sketch of the workpiece identifing the surfaces affected by the operation. For example, in the case of a plating or nitriding operation, the workpiece surfaces involved would be identified.

Detail data generated for metalcutting operations specify the machine tool, cut sequence, type of cutter tools, suggested feeds and speeds, and a dimensioned sketch of the workpiece identifying the machined surfaces. Data specifying special fixtures or clamping tools required by the operation are not output by the current system -- this data will have to be added by the process planner. Also, tool holders, cutter holders, chip breakers, turning heads and blocks will normally have to be added by the process planner.

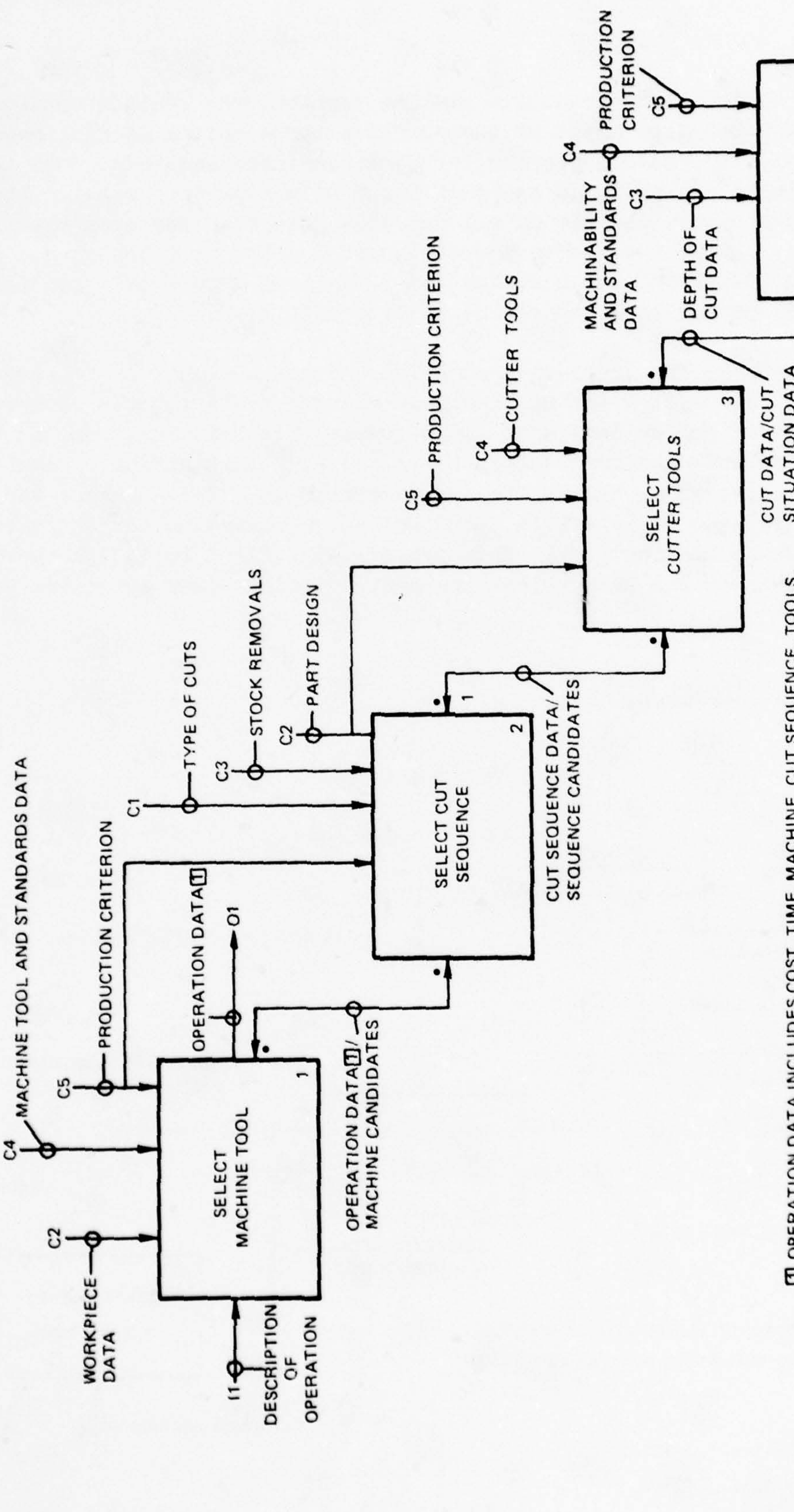
As will be seen in later diagrams, the planning of a metalcutting operation involves much analysis because of the interrelated nature of the factors involved. The machine tool, cut sequence, cutter tools and machining parameters are determined only after alternative solutions have been considered in terms of production rate and cost. To do the analysis, data is required about production requirements, machine tools, cutter tools, machinability, standards and stock removal allowances.

The third function provides the process planner with the opportunity to accept or modify the detail operation data generated by the system. If the option is not requested, the system will automatically accept the operation data. When the function is activated, the process planner can add data or make changes to the detail data. For example, cutter tools could be added where they were not automatically selected by the system -- also, cutter holders, tool holders, etc. could be added.

Generate Data for Metalcutting Operations (A32)

Diagram A32 shows that the function to generate data for metalcutting operations is factored into four parts: select machine tool; select cut sequence; select cutter tools; and determine cut parameters. Each part presents a problem whose solution is dependent on solving the other problems. That is, selection of a machine tool is dependent on knowing the cut sequence, cutter tools, and feeds, speeds, and depth of cuts. Similarly, the best cut sequence is dependent on the choice of machine tool and the selected tool combination. The choice of cutter tools is dependent on machine tool, workpiece material, cut geometry, feed, speed, depth, tolerance and finish. The selection of feeds and speeds is dependent on all of the above variables and in addition includes consideration of the tool material and geometry, cutting forces, and machine tool operating limits.

The CPPP system has been designed to solve the individual problems of machine selection, cut sequence selection, tool selection and cut parameter selection simultaneously. The first function selects a machine tool based on the input description of the operation and the detail sequence data developed for each candidate machine tool. The data channel entering the first box from the right carries detail operation data generated by the second function -- channels in which data can pass in two directions are identified by a dot



[1] OPERATION DATA INCLUDES COST, TIME, MACHINE, CUT SEQUENCE, TOOLS, FEEDS, SPEEDS, AND CUTTING DEPTHS

DIAGRAM A32

placed next to the arrow head. In similar fashion, the second function selects a cut sequence based on input of the surfaces to be cut, a machine candidate, and the detail tool data generated for each candidate sequence. The third function selects cutter tools based on input of a candidate machine tool, candidate cut sequences, and the detail cut data generated for each type of cut and candidate cutter tool. The fourth function determines detail cut data (feed, speed, depth of cut, cost and time) based on inputs of a candidate machine tool, cutter tool and cut definition data.

The procedure for generating detailed operation plans can be summarized as follows: 1) select a set of candidate machine tools for the described operation; 2) determine candidate cut sequences for removing metal on each machine; 3) select candidate cutter tools for each combination of machine tool and cut sequence; 4) determine the cut parameter data for each cut and tool of a cut sequence; and 5) select in turn the best combination of cutter tools, cut sequence and machine tool. This process will first build a network of possible solutions and then select the best solution based on either production rate or cost.

Select Machine Tool (A321)

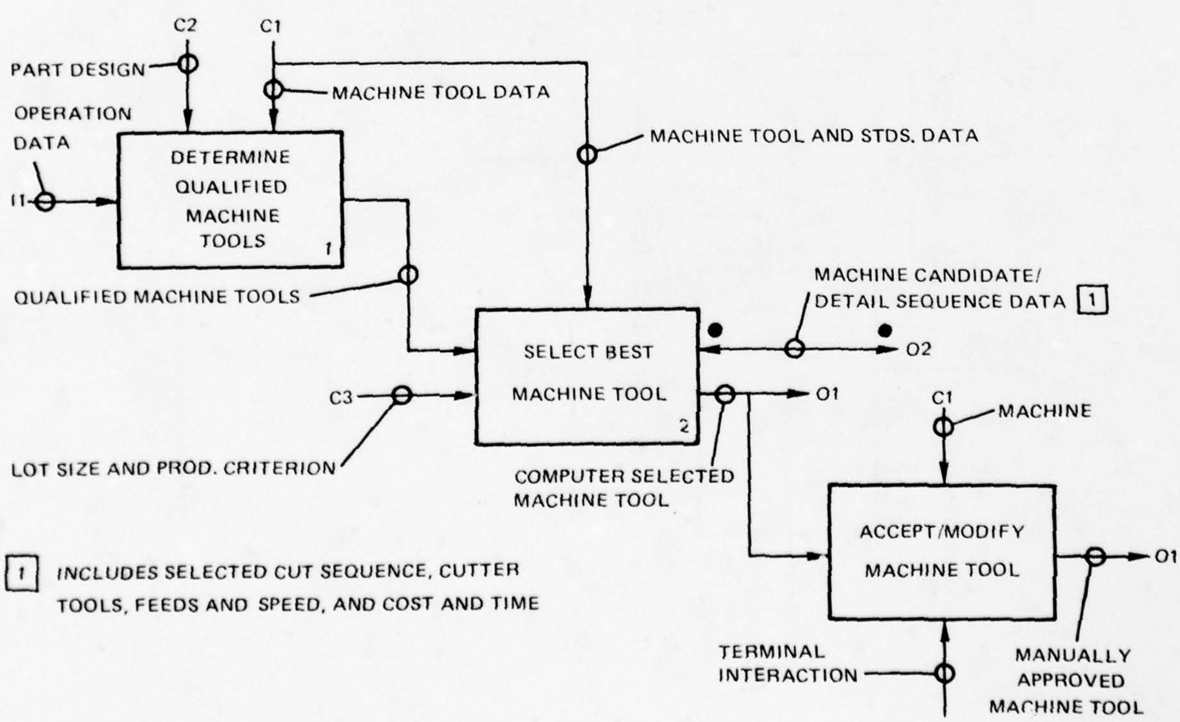


Diagram A321 shows that the function to select a machine tool for a defined operation is factored into three parts: determine qualified machine tools; select best machine tool; and accept/modify selected machine tool. This set of functions will identify machine tools qualified for the operation, determine times and costs associated with each machine tool, and select the machine tool satisfying the production criterion. The first function will qualify machines based on the cuts to be made, the type of machine tool specified in the operation, and the workpiece size. The machine tools of a workshop are classified by categories such as engine lathes, turret lathes, automatics, centerless grinders, surface grinders and gun drills. In the case where a specific machine tool is specified in the operation data, only that machine will be considered.

The second function selects the best machine tool based on optimum production rate or cost. Before a selection can be made, the operation must be detailed for each candidate machine tool. Therefore, the best cut sequence, tools, feeds and speeds and cutting time and cost must first be determined for each machine. This data combined with information about lot size and setup cost/time will enable a machine tool to be selected. Production time and cost per piece are calculated from the following equations:

$$t_p = t_s + \sum_{cuts} (t_c + t_t) + t_i \tag{1}$$

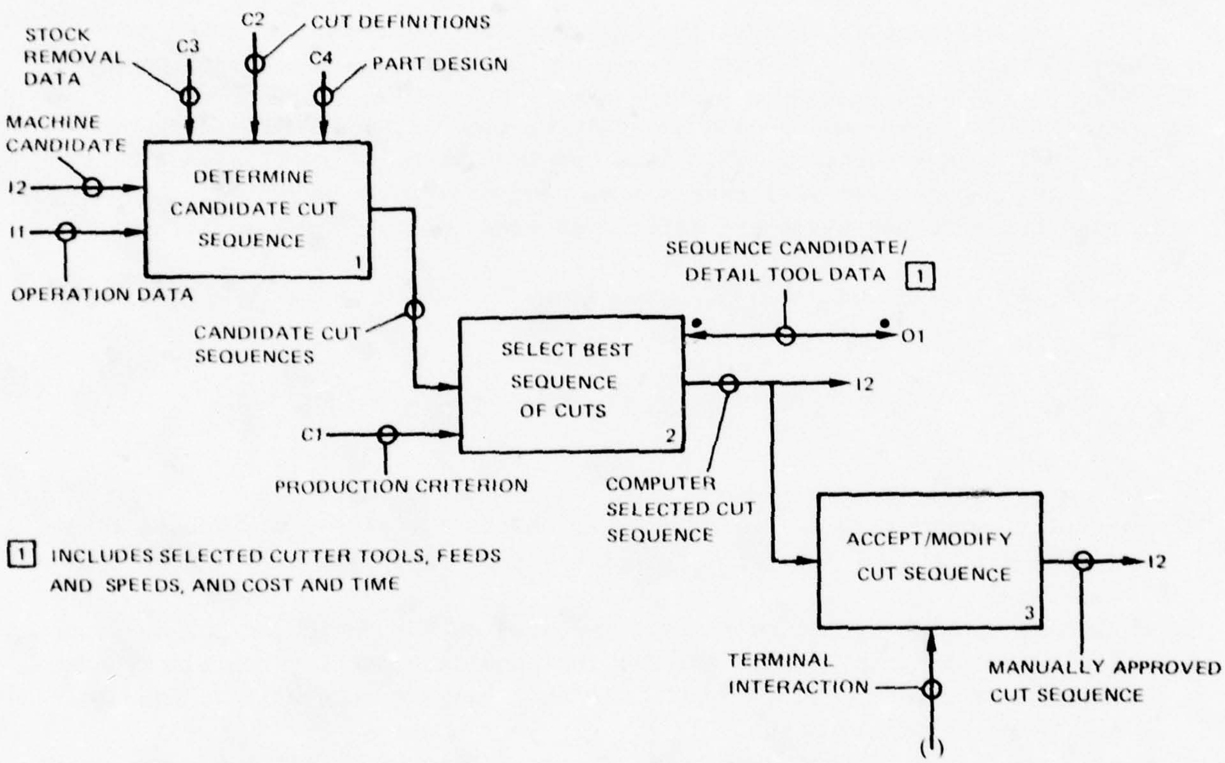
$$c_p = c_\ell \, t_s + c_m \sum_{cuts} (t_c + t_t) + c_m t_i + c_\ell t_o + c_t \tag{2}$$

t_p = time of operation per piece
t_s = setup time per piece -- this is based on the lot size and standard time calculation. (machine setup/lot size + tool setup/lot size + workpiece handling)
t_c = time of cutting operation -- this is based on the choice of cut sequence, tools and machining parameters for the candidate machine tool; as seen in the diagram, the time and cost of the best cut sequence will be calculated and input to this function.
t_t = time allocated to tool change per piece -- this is based on the number of cuts that can be made with a sharp tool; the time is determined in the select cut parameter function and input to this function.
t_i = internal machine time -- this is time lost due to tool travel and indexing; it is based on the tool layout and can be determined from the standard time calculation.
t_o = internal operator time -- this is time spent by the operator attending the machine tool in operation (machine control, tool change, gaging); it is determined from the standard time calculation.
c_p = cost of operation per piece
c_ℓ = labor direct and overhead cost
c_m = machine direct and overhead cost

c_t = cutter tool cost -- this is determined from the number of parts that can be machined with a single cutter edge; a proportion of all cutter tool cost is allocated to each operation.

The third function provides the process planner with the opportunity to accept or change the selected machine tool. If the option is not requested, the system will automatically accept the chosen machine.

Select Cut Sequence (A322)



This diagram shows that the function to select a cutting sequence is factored into three parts: determine candidate cut sequences; determine best sequence of cuts; and accept/modify selected sequence of cuts. Theoretically, material can be removed using several combinations of cuts. Since the best sequence of cuts cannot always be determined a priori, the system must first determine possible sequences for removing the material and then determine the time and cost associated with each candidate sequence.

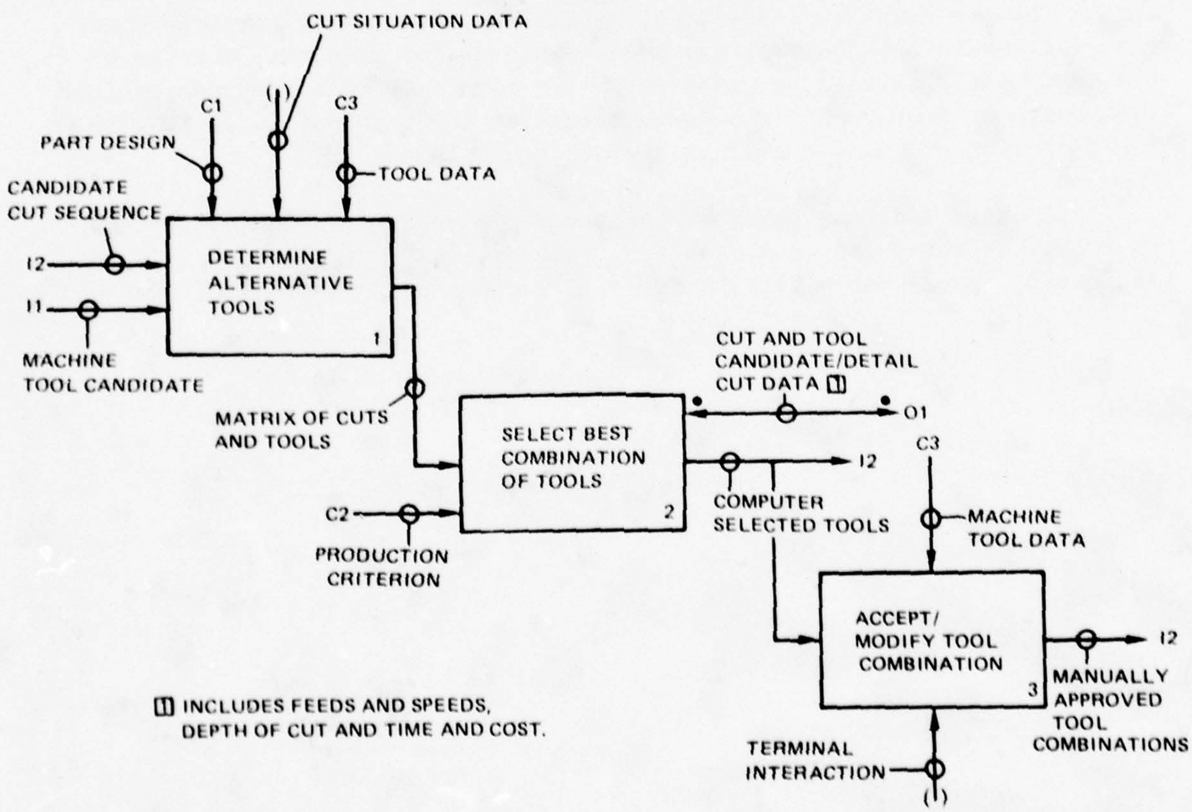
The first function will determine a set of candidate cut sequences. For

each sequence, the specific type of cuts and their order will be defined. Also, the cut situation data defining each cut in a sequence will be produced -- this data specifies for each type of cut the amount of stock to be removed.

The second function will determine which of the candidate cut sequences is best. Since the decision must be based on some economic criterion, it is necessary to first calculate the time and cost associated with each cut sequence -- this calculation is dependent on the selection of cutter tools and determination of feeds, speeds, and depth of cuts. The time and cost data for each cut sequence is determined in other parts (A323 and A324) of the system. When the data has been generated for all candidate cut sequences, the best cut sequence is chosen.

The third function provides the process planner with the opportunity to accept or modify the selected sequence of cuts. If the option is not requested, the system will automatically accept the selected cut sequence.

Select Cutter Tools (A323)



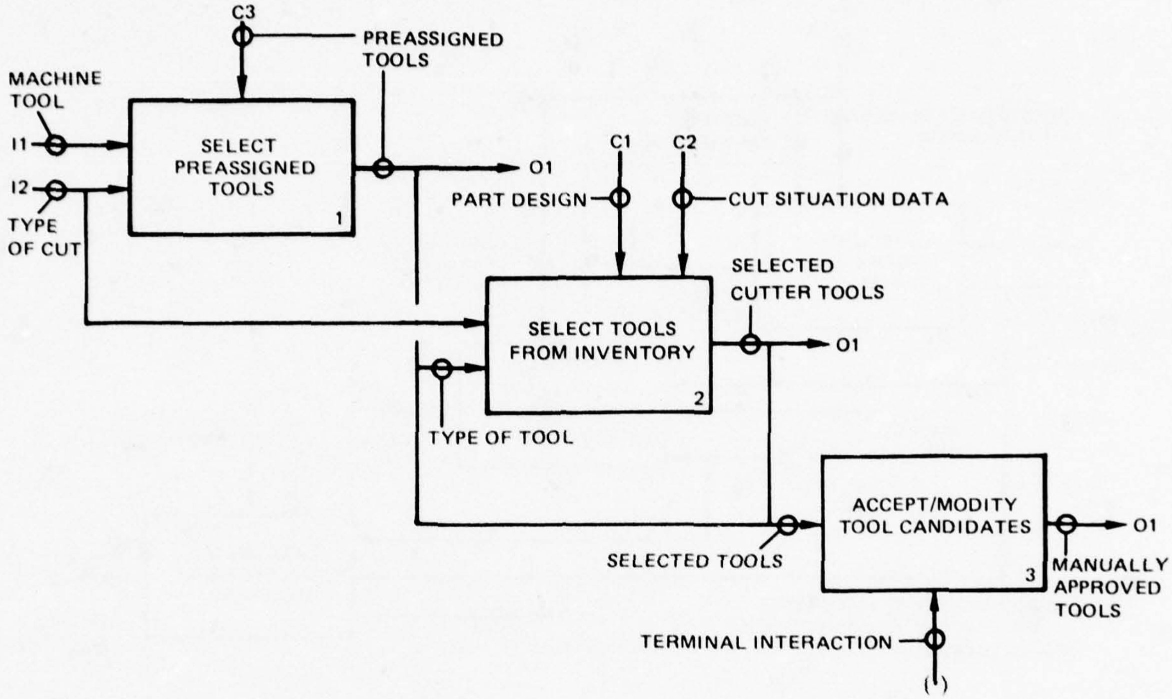
This diagram shows that the function to select cutter tools is factored into three parts: determine alternative tools, select best combination of tools, and accept/modify tool combination. The primary objective is to determine the combination of tools for a cut sequence that will give the best machining performance. There are several factors to consider. First, there may be several cutter tools of different material and geometry that can be used to make a cut. Second, some tools may be able to be used in more than one cut -- this can reduce both the number of tools required and the tool indexing.

The first function will determine the alternative tools for a candidate cut sequence. Candidate cutter tools are selected for each type of cut selected in the cut sequence. The process of selecting cutter tools is controlled by the cut situation data specified for each type of cut and the tools preassigned for certain types of cut.

The second function will determine the best set of tools for the cut sequence. To make the decision it is first necessary to calculate the time and cost associated with each type of cut and candidate tool. This calculation is done by the function (A324) that determines the cutting parameters for each cut. When the analysis has been completed for each cut, a table of time and cost data will be constructed for candidate tool combinations and the choice of best tools is made by selecting the combination satisfying the criterion of maximum production rate or minimum cost.

The third function provides the process planner with the opportunity to accept or change the selected tool combinations. If the option is not requested, the system will automatically accept the selected tool combination.

Determine Alternative Tools (A3231)

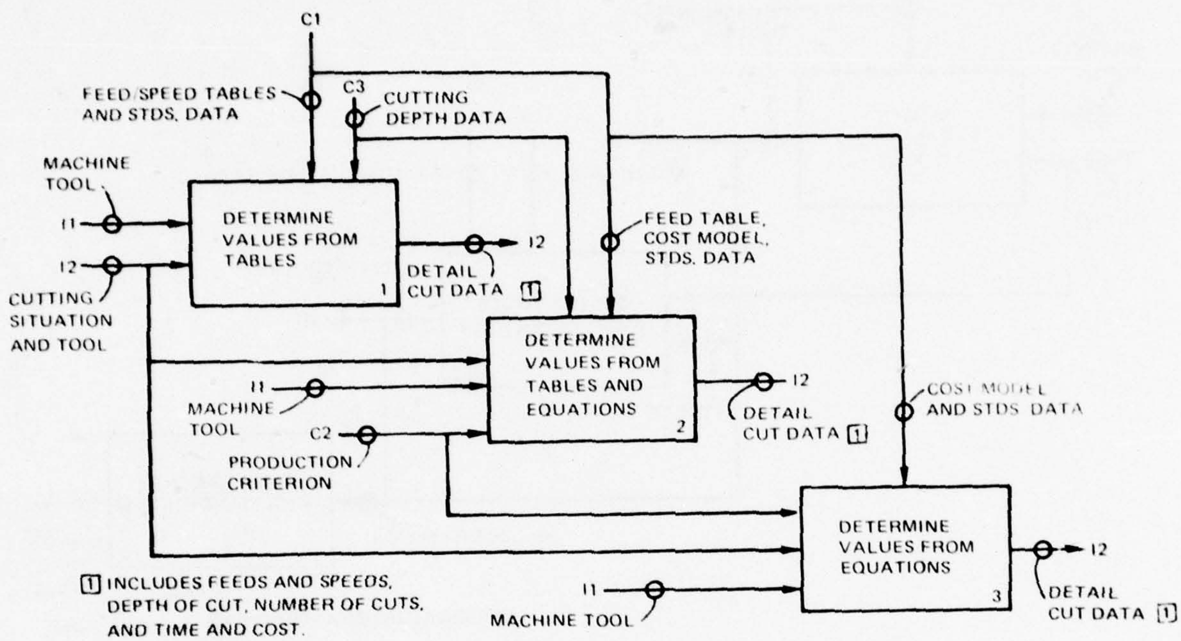


This diagram shows that the function to select alternative tools is factored into three parts: select preassigned tools, select tools from inventory, and accept/modify tool candidates. The first two functions will select candidate tools for specific types of cuts. The first function will select preassigned tools for different types of cuts made on a specific machine tool. In addition to cutter tools, cutter and tool holders, chip breakers, heads and blocks can also be selected.

The second function (not available in current system) will select cutter tools from inventory as described in the data base. This function is activated whenever tools are not preassigned or only a general type of tool has been specified. Cutter tools are selected from inventory according to the type of cut and specific cutting situation. In the situation where the system fails to select a candidate tool for a cut, the process planner is required to specify a tool.

When all tool candidates have been selected, the third function will provide the process planner with the opportunity to accept or modify the chosen tool candidates. This function permits the process planner to specify new tools or delete tools from further consideration. If the option is not requested, the system will automatically accept the selected tool candidates.

Select Cut Parameters (A324)



This diagram shows that the function to select cut parameters for different types of cuts is factored into three parts: determine values from tables, determine values from tables and equations, and determine values from equations. Each of these subfunctions provide alternative methods for analyzing cutting time and cost. The basic equations involved are shown below:

$$\text{time} = \frac{v}{R} + \frac{vt}{RT} \qquad (1)$$

$$\text{cost} = \frac{c_\ell v}{R} + \frac{c_\ell vt}{RT} + \frac{c_t v}{RT} \qquad (2)$$

v = volume -- the amount of material removed by a cut

t = time to change a worn tool

c_ℓ = labor direct and overhead cost

c_t = cutter tool cost per cutting edge

R = cutting rate

T = tool life

Although the equations are simple, the problem of determining values for cutting rate (R) and tool life (T) is not simple. In the most rigorous treatment of these variables, they are quantitatively defined by a multidimensional space relating speed, feed, depth of cut, finish, tolerance, workpiece material, tool material and geometry, and other variables. Unfortunately, the data is often not available in a workshop to develop accurate correlations between variables. Therefore, a computer process planning system must provide several ways of approaching the machining analysis problem; three methods have been specified of which only the first is available in the current system.

In the first approach feeds, speeds and depth of cut are determined from tables prepared by manufacturing. This part of the system also estimates tool life for different combinations of workpiece and tool materials. It is assumed that the tool life data will be correlated with the feed and speed tables, and therefore, can be used to estimate the number of cuts (and parts) that can be made with one cutting edge. The second approach is specified to use equations relating cutting speed and tool life for different types of cuts, machine tools, workpiece and tool materials, depth of cut, tool geometry, tolerance and finish conditions. Coefficient data is needed for equations of the following form:

$$VT^n = c \qquad (3)$$

Other forms of equations could also be accommodated by making changes to the system. The cutting feed would be determined from tables.

The third approach is specified to use equations from which the optimum combination of feed, speed and depth would be determined. As improved machinability models relating cutting parameters of tool life and cutting rate become available, optimization techniques can be added to the system.

In each approach the process planner can interact with the system to accept or modify values that are automatically determined by the system. Data values are displayed for number of cutting passes, depth of cut, feed, speed, rate, time, cost, tool life, volume of material removed, tool material, rake angle, tool cost, number of parts cut per tool edge, horsepower, spindle torque, and resultant cutting force. If this function is activated, the process planner can independently set feed, speed and depth of cut values and the system would use them in the cutting analysis.

APPENDIX B

INTERACTIVE DISPLAYS

Though CPPP can be used in a batch processing mode, it is most often operated from a graphic terminal. There are fifteen interaction points at which the process planner can influence CPPP planning (Section 2.5). Most of these are optional -- the process planner can choose whether he wishes to review/modify the CPPP decisions associated with the interaction point.

Operation of the CPPP terminal is described in this appendix. Each interaction point is discussed, using an example of the terminal display that appears at the interaction point.

Terminal Operating Procedures

CPPP is currently implemented for TEKTRONIX 4006, 4010, 4012, and 4014 graphic terminals. From the user's point of view, the terminal contains two or three basic elements -- a cathode ray tube screen, an alphanumeric keyboard, and probably a hardcopy device. Information and instructions from the CPPP computer to the process planner are displayed on the television-like screen. The process planner sends directions to CPPP using the typewriter-like keyboard. The hardcopy device enables the user to save a copy of any display for later reference.

The screen is of the "storage" type rather than the "refreshed" type. That is, a portion of the screen surface remains activated or bright until "erased", rather than requiring periodic reactivation. Storage terminals are far less expensive than refreshed ones, but do not have the capability to be selectively erased. To delete or modify any portion of a display, the screen is completely erased and redrawn. For the CPPP application, it is felt that selective erasure is a minor convenience which is far outweighed by the lower terminal cost.

The process planner inputs directions and data by typing them on the keyboard. He signals the end of a message by depressing the RETURN key. As he types his message, it is displayed on the screen. The message can be aborted at any time before the RETURN is typed by simultaneously depressing the CTRL (CONTROL) and X keys. The message can be restarted immediately after doing so. The most recent character entered may be deleted by simul-

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taneously depressing the CTRL and Z keys. This may be done repetitively to delete several characters. (Deleted messages and characters remain on the screen but are ignored by the computer.)

The terminal may have a hardcopy device attached to it. If so, a copy of the current display can be obtained by pressing the COPY key in the upper right portion of the keyboard.

Interaction Points

The remainder of this appendix contains a discussion of each CPPP interaction point. The context in which the interaction point occurs is related and user options are described. An example of the primary display at the interaction point is given. (Some of the options offered by primary screens cause subordinate displays to appear.) Process planner messages may be distinguished in the examples by the symbol > in the left margin.

Each screen offers a list of options available to the process planner. If an option requires data from the process planner, the option list indicates the required data. For example, the option for adding cutter tools might appear as follows:

4, CUT ID, LIST OF NEW CUTTER TOOL CANDIDATES

If the process planner wished to add the cutters 1203-006 and 1203-012 for consideration in the third cut shown in the particular display, he would type

4,3,1203-006,1203-012

Interaction Point 1

```
UTRC CPPP SYSTEM.  INITIATE METHOD OF PROCESS PLANNING.
TYPE IN METHOD OF PROCESS PLANNING, YOUR NAME, PART NUMBER
  1 NEW PLAN, WITH OPERATIONS GENERATED BY PROCESS DECISION RULES
  2 NEW PLAN, WITH OPERATIONS GENERATED INTERACTIVELY
  3 RESUME PLANNING SESSION (NOT YET AVAILABLE)
  4 EDIT COMPLETED PROCESS PLAN (NOT YET AVAILABLE)
>1,MARK DUNN,747917-20
```

The process planner selects the method of CPPP planning he desires. Two methods are currently offered, both for development of a new process plan. In the first, the summary of operations is generated by a process decision model with or without the assistance of the process planner. In the second, the process planner composes the summary of operations by repetitive use of interaction point 4. The input message shows that the first option is chosen to plan a process for part 747917-20.

The display indicates two additional process planning methods that could be implemented in the future -- resumption of a CPPP session that was suspended and modification of an existing process plan.

Interaction Point 2

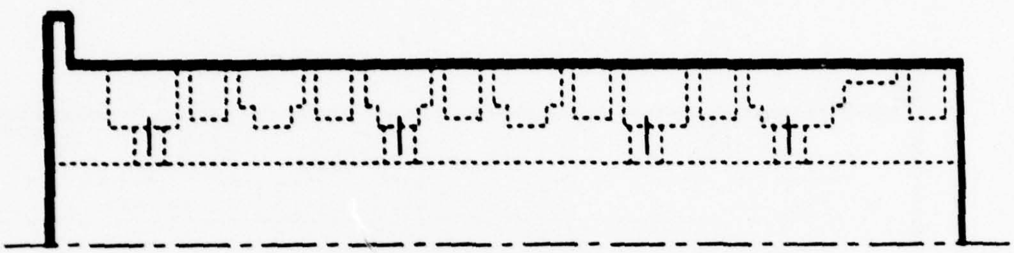
```
UTRC CPPP SYSTEM.  INITIATE STARTUP DATA FOR NEW PLAN.

TYPE IN LOT SIZE, CRITERION FOR DECISION MAKING.  (1 FOR MINIMUM COST,
2 FOR MINIMUM TIME):
>50,1
TYPE IN NUMBERS OF DESIRED INTERACTION POINTS OR TYPE C/R FOR FULLY
AUTOMATIC PLANNING:
  1 ACCEPT/MODIFY GENERATED OPERATION (DECISION RULES)
  2 ACCEPT/MODIFY SEQUENCE OF OPERATIONS
  3 ACCEPT/MODIFY MACHINE TOOL CANDIDATES
  4 ACCEPT/MODIFY CUT SEQUENCE CANDIDATES
  5 ACCEPT/MODIFY CUTTING TOOL CANDIDATES
  6 ACCEPT/MODIFY MACHINING DATA
  7 ACCEPT/MODIFY SELECTED TOOL COMBINATION
  8 ACCEPT/MODIFY SELECTED CUT SEQUENCE
  9 ACCEPT/MODIFY SELECTED MACHINE TOOL
 10 ACCEPT/MODIFY DETAILED OPERATION PLAN
 11 ACCEPT/MODIFY FINAL PROCESS PLAN DATA
>1,2,3,4,5,6,7,8,9,10,11
TYPE OPERATION NUMBERS TO BEGIN AND END INTERACTION WHEN PLANNING
SEQUENCE OF OPERATIONS, OR C/R FOR ALL OPERATIONS:
>20,110
TYPE OPERATION NUMBERS TO BEGIN AND END INTERACTION WHEN PLANNING
DETAIL OPERATION DATA, OR C/R FOR ALL OPERATIONS:
>20,110
```

Information required to develop a new process plan is entered. The lot size is provided and the process planner states whether decisions with respect to the selection of machines, tools, etc. should be based on minimum production cost or time.

The process planner specifies the level of interaction desired by entering the interaction points he wishes to use. Selection of an optional interaction point enables him to review and accept/modify the associated CPPP decisions. He may request the interaction for the entire plan or some portion of it. The above example shows that interaction is requested beginning with Operation 20 and ending with Operation 110. Also, interaction is requested in both the planning of a sequence of operations and detail planning of operations.

Interaction Point 3

```
UTRC CPPP SYSTEM.  ACCEPT/MODIFY GENERATED OPERATION
OP.   20  DESCRIPTION: TURN
MACH. CLASS 1:  400 BAR MACHINE                    MACH. CLASS 2: (NONE)
MACHINE TOOL SPECIFIED: (NONE)
```



```
LOFOFOGRGGGWGGGRGGGWGGRGGGGRGRD
E00000RHRRRORRRHRRRORRHRRRRHRE0
0000000111122223334445556666 7788
1234567026925925825815804581601
X  XXX                        X
TYPE C/R TO ACCEPT OPERATION, OR TYPE AN OPTION, AND REQUIRED DATA
1.NEW OP DESCRIPTION   2.MACHINE CLASS NUMBER (1 OR 2).CODE.NAME
3.MACHINE TOOL CODE.NAME   4.LIST OF ADDED CUTS  5.LIST OF DELETED CUTS
6 (CHANGES SETUP)   7 (DELETES OPERATION)   8 (SHOWS MACHINE DATA)
9 (TERMINATES PLANNING)
8
```

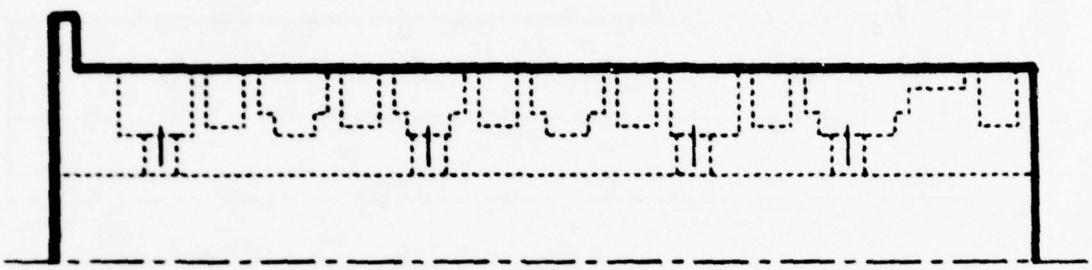
At this interaction point, the process planner reviews an operation generated by a process decision model. The display appears immediately after the operation is generated, before subsequent operations are defined. Therefore, any user-specified changes are taken into account in the execution of the remainder of the process model.

The operation description and machine class(es) to be considered (or specified machine tool) are shown. The part surfaces/features to be cut or processed are indicated by heavy lines in the workpiece sketch and by X's in the surface/feature name list. The sketch is oriented so that the free end is to the right.

The process planner can change any of the data associated with the operation. He can choose to delete it entirely.

Interaction Point 4

```
UTRC CPPP SYSTEM.  INTERACTIVELY DEFINE OPERATION
OP.   20  DESCRIPTION: TURN
MACH. CLASS 1:     0                              MACH. CLASS 2: (NONE)
MACHINE TOOL SPECIFIED: (NONE)
```

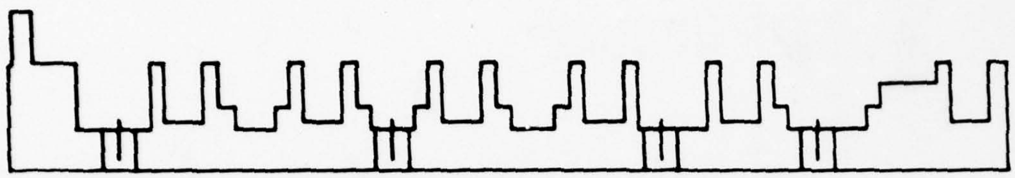


```
LDFDFDGRGGGWGGGRGGGWGGRGGGGRGRD
E00000RHRRRDRRRHRRRDRRHRRRRHRE0
0000000111122233344455566667788
1234567026925925825815804581601
X  XXX                        X
TYPE C/R TO ACCEPT OPERATION; OR TYPE AN OPTION, AND REQUIRED DATA
1,NEW OP DESCRIPTION   2,MACHINE CLASS NUMBER (1 OR 2),CODE,NAME
3,MACHINE TOOL CODE,NAME   4,LIST OF ADDED CUTS  5,LIST OF DELETED CUTS
6 (CHANGE SETUP)  7 (SHOW MACHINE DATA)  8 (END SEQUENCE OF OPERATIONS)
9 (TERMINATES PLANNING)
>2,1,400,BAR MACHINE
```

By repetitive use of this interaction point, a sequence of operations is generated without a process decision model. Before an operation is defined, the display appears without operation data specified and with the current workpiece shape shown in the sketch. If no more operations are desired, option 8 is used to signal completion of the sequence of operations. Otherwise, options 1 through 6 are used to define another operation. RETURN is typed to indicate completion of an operation. The operation data is then stored by CPPP and the definition of a new operation can begin.

Interaction Point 5

```
UTRC CPPP SYSTEM.  ACCEPT/MODIFY SEQUENCE OF OPERATIONS
```



```
          LDFDFDGRGGGWGGGRGGGWGGRGGGGRGRD
          E00000RHRRRDRRRHRRRDRRHRRRRHRE0
          00000001111222333444555666667788
          1234567026925925825815804581601
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  60 TURN                               AUTOMATIC CHUCKER  N/C LATHE
     1111000000000000000000000000000
  70 HAND REAM THRU BORE                BENCH LAP
     0000000000000000000000000000001
  80 HONE THRU BORE                     AUTOMATIC HONE
     0000000000000000000000000000001
  90 GRIND LONGEST OD                   OD GRINDER
     0000110000000000000000000000000
 100 GRIND FREE END                     SURFACE GRINDER
     1000000000000000000000000000000
(THERE ARE MORE OPERATIONS)

     TYPE C/R TO ACCEPT SEQUENCE OR TYPE AN OPTION AND REQUIRED DATA
 1 (SHOW MORE OPS)   2 (SHOW PREVIOUS OPS)   3 (SHOW MACHINE DATA)
 4,OP. NUMBER (HIGHLIGHT CUT SURFACES)   5,NOT AVAILABLE
 6,NOT AVAILABLE              7,OP. NUMBER (TO DELETE)   8 (TERMINATE)
>1
```

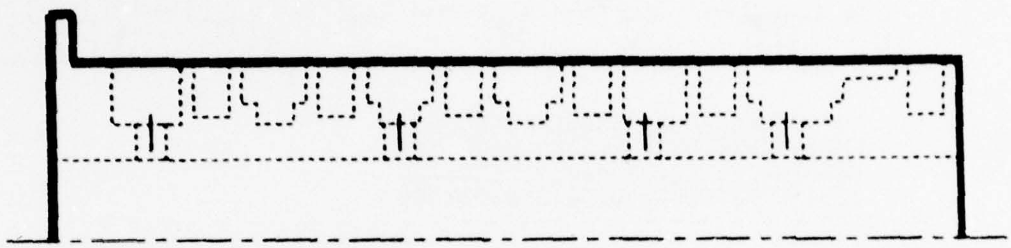
The sequence of operations can be reviewed and modified at this interaction point.

The sketch shows the final workpiece shape. Data for operations, in sets of five, are displayed -- operation number, description, machine class, second machine class or specified machine tool, and surfaces/features cut or processed. The latter are indicated by "1" under the surface/feature name.

Options 1 and 2 permit paging to the next and previous sets of five operations. At present, the process planner can modify the sequence only by deleting operations. Future options could permit modification of any operation data as well as addition of operations.

Interaction Point 6

```
UTRC CPPP SYSTEM.  ACCEPT/MODIFY MACHINE TOOL CANDIDATES

OP   20   DESCRIPTION: TURN
MACH CLASS 1: BAR MACHINE
```



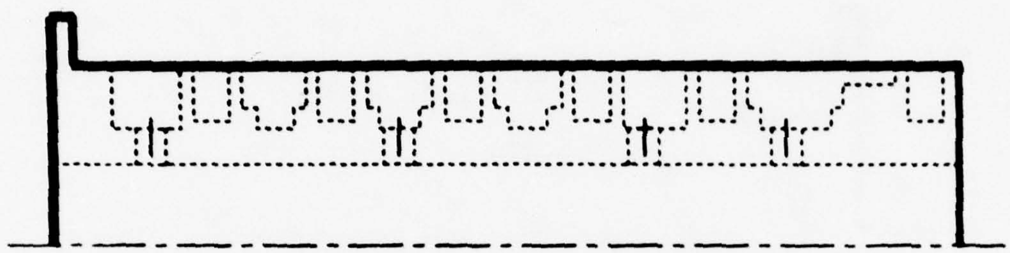
```
MACHINE TOOLS TO BE CONSIDERED FOR THE OPERATION ARE
 401 B&S NO 4 AUTOMATIC                403 TABER
 404 PETERMAN P25

HIT C/R TO ACCEPT CANDIDATES OR TYPE AN OPTION AND REQUIRED DATA
1,LIST OF MACHINE CODES TO BE DELETED   2 (SHOW MACHINE DATA)
>1,403
```

The machine tools to be considered for an operation are displayed. The process planner can eliminate machine tools from consideration. An option to add candidates could be provided in the future.

Once the process planner approves the list of candidate machines, the operation is detailed for each. Cost and time are calculated for each machine and a choice is made.

Interaction Point 7

```
UTRC CPPP SYSTEM. ACCEPT/MODIFY CUT SEQUENCE CANDIDATES.
OP   20   DESCRIPTION: TURN
CANDIDATE MACHINE TOOL: B&S NO.4 AUTOMATIC
```



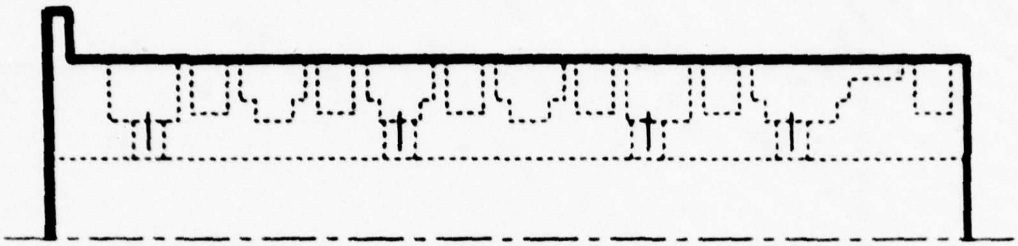
```
CUT SEQUENCES TO BE CONSIDERED FOR THIS MACHINE ARE:
 1 D004 D006 F005 RE80 LE01
 2 D004 RE80 D006 F005 LE01
 3 D006 F005 RE80 D004 LE01

HIT C/R TO ACCEPT CANDIDATES OR TYPE IN OPTIONS AND REQUIRED DATA
1.SEQUENCE OF SURFACE ELEMENT NAMES TO BE ADDED
2.LIST OF CUT SEQUENCE ID'S TO BE DELETED
2,3
```

The cut sequences to be considered in performing an operation on a candidate machine tool are displayed. The process planner can remove sequences from consideration or specify additional candidates.

After the list of candidate cut sequences is final, the operation is planned for each sequence on the machine being considered. Cost and time are calculated and the best sequence is chosen.

Interaction Point 8

```
UTRC CPPP SYSTEM   ACCEPT/MODIFY CUTTING TOOL CANDIDATES

OP   20   DESCRIPTION: TURN
CANDIDATE MACHINE TOOL: B&S NO.4 AUTOMATIC
```



```
ID  CUT   CUT TYPE                          CUTTER CANDIDATES
--  ----  ------------------   ------------------------------------------
 1  D004  TURN OPN DIA   (TO)  1 1203-001              2 1203-003
                               3 1203-005
 2  D006  TURN & FORM    (TS)  1 1203-001              2 1203-003
    F005                       3 1203-007
 3  RE80  FACE OPEN      (FO)  1 1203-002              2 1203-004
                               3 1203-006
 4  LE01  CUTOFF         (CO)  1 1207-001              2 1207-002

  (THERE ARE NO MORE CUTS)

HIT C/R TO ACCEPT CANDIDATES OR TYPE AN OPTION AND REQUIRED DATA
1 (SHOW MORE CUTS)  2 (SHOW PREVIOUS CUTS)
3 CUT ID, LIST OF CUTTER ID'S TO BE DELETED
4 CUT ID, LIST OF NEW CUTTER TOOL CANDIDATES
5 CUT ID, LIST OF NEW CUTTER TYPE CANDIDATES
>4,3,1203-005
```

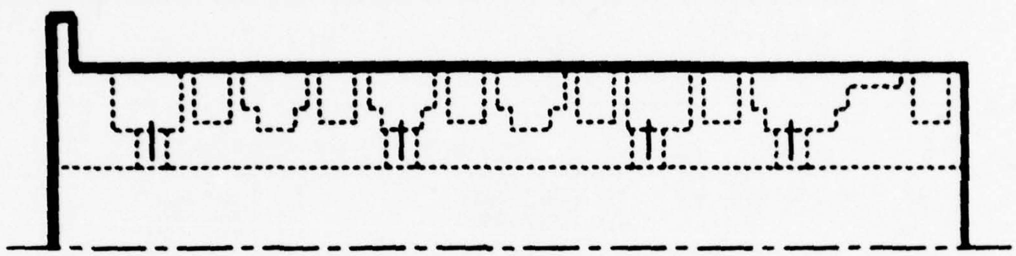
After candidate cut sequences have been determined for a candidate machine, the types of cuts are determined. Cutter tools to be considered for each cut are then determined. The candidate cutters may be particular tools or tool types.

The display shows, in order, the cuts to be made. The surfaces cut, type of cut, and candidate cutters are given. The process planner can remove cutters from consideration or insert new candidates. The above example shows that cutter 1203-005 is to be added to the candidates for cut number 3 (Face Open).

After the cutter candidates are accepted, machining parameters are determined for each candidate.

Interaction Point 9

```
UTRC CPPP SYSTEM.  ACCEPT/MODIFY MACHINING DATA.

OP   20   DESCRIPTION:  TURN
CANDIDATE MACHINE:  B&S NO.4 AUTOMATIC       CUT TYPE: TURN OPN DIA  (TO)

CANDIDATE CUTTER:  1203-003                  SURFACE(S):  D004
```



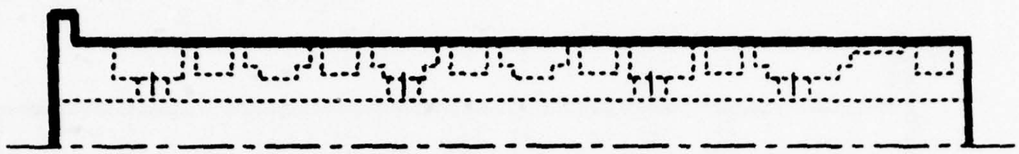
```
 01 NO. OF PASSES =     1           10 VOLUME REMOVED =   .05 CU IN
*02 CUT DEPTH = .008 IN             11 RAKE ANGLE = 0. DEG
*03 FEED = .005 IPR                 12 NOSE RADIUS = .000
*04 SPEED = 2226.RPM                13 TOOL MATERIAL =C6
 05 CUT RATE =  .195 CU IN/MIN      14 COST/EDGE = $  .00
 06 CUT TIME =  .36 MIN             15 FORCE ON TOOL TIP =  .00
 07 CUT COST = $  .00               16 HORSEPOWER =  .00
 08 TOOL LIFE = 30.0 MIN            17 SPINDLE TORQUE =  .00
 09 PARTS PER TOOL =  83

TYPE C/R TO CONTINUE
>
```

The machining data for a candidate cutting tool are displayed. Several parameters are not currently calculated. These can be added in the future.

At present, the process planner is not able to modify the CPPP-determined machining parameters. Future enhancements could permit him to change independent parameters (e.g., feed and speed), with automatic recalculation of dependent values.

Interaction Point 10

```
UTRC CPPP SYSTEM. ACCEPT/MODIFY SELECTED TOOL COMBINATION

OP   20   DESCRIPTION:  TURN
CANDIDATE MACHINE TOOL:  B&S NO.4 AUTOMATIC
SEQUENCE:  D004 D006 F005 RE80 LE01
CUT TYPE:  TO   TS        FO   CO
```



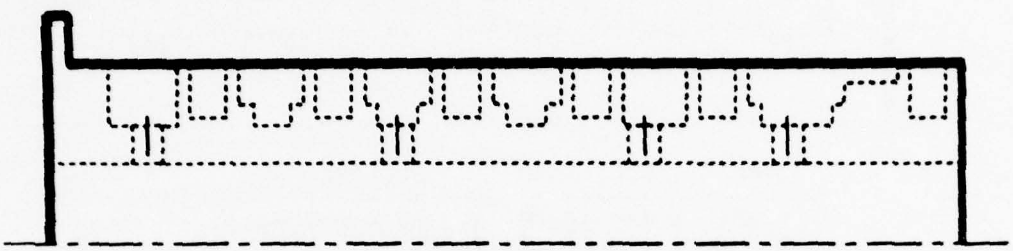
```
TIME       COST      ID          CANDIDATE CUTTER COMBINATIONS
------   --------    --   ----------------------------------------------
 8.00    $ 150.00    17   TO 1203-003              TS 1203-007
                          FO 1203-004              CO 1207-001

 8.50    $ 175.00    18   TO 1203-005              TS 1203-007
                          FO 1203-004              CO 1207-001

 8.25    $ 149.66    19   TO 1203-001              TS 1203-001
                          FO 1203-006              CO 1207-001

 8.00    $ 149.66    20   TO 1203-003              TS 1203-001
                          FO 1203-006              CO 1207-001

(THERE ARE MORE CANDIDATE COMBINATIONS)
COMBINATION 19 HAS BEEN CHOSEN FOR MINIMUM COST

TYPE C/R TO ACCEPT CHOICE OR TYPE AN OPTION AND REQUIRED DATA
1 (SHOW MORE DATA)    2 (SHOW PREVIOUS DATA)    3,ID OF PREFERRED CHOICE
>2
```

Identification of candidate cutting tools for each cut determines a number of possible tool combinations. If there are four cuts with two, four, three, and two cutter candidates, for example, then there are forty-eight possible tool combinations. Using time and costs calculated for each candidate cutter, CPPP determines the time and cost for each tool combination (to a maximum of 30 combinations).

At this interaction point, each tooling combination that was evaluated is displayed. The time and cost associated with each is shown and CPPP's choice is given. The process planner can examine this data, paging forward and backward with options 1 and 2. Option 3 permits him to override CPPP's choice. Once the choice is finalized, the cutter tools for the current machine tool and cut sequence are determined.

Interaction Point 11

```
UTRC CPPP SYSTEM. ACCEPT/MODIFY SELECTED CUT SEQUENCE.

OP   20   DESCRIPTION: TURN
CANDIDATE MACHINE TOOL: B&S NO.4 AUTOMATIC
```



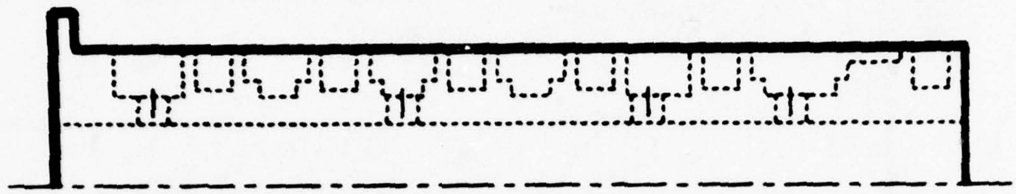
```
TIME     COST    ID              CANDIDATE CUTTING SEQUENCES
------   ------  --  -----------------------------------------------
8.251 $ 149.66    1 D004 D006 F005 RE80 LE01
8.612 $ 175.00    2 D004 RE80 D006 F005 LE01
(THERE ARE NO MORE CANDIDATE SEQUENCES)

SEQUENCE  1 HAS BEEN CHOSEN FOR LOWEST COST

HIT C/R TO ACCEPT CHOICE OR TYPE AN OPTION AND REQUIRED DATA:
1 (SHOW MORE CUT SEQUENCE DATA)  2 (SHOW PREVIOUS CUT SEQUENCE DATA)
3,ID OF PREFERRED CHOICE  4,ID OF CUT SEQ. (SHOW SELECTED TOOLS)
>4,2
```

This interaction point occurs after cut types, tooling, and machining parameters are determined for each candidate cut sequence. CPPP chooses the best sequence on a time or cost basis. The candidates and the choice are displayed. The time and cost calculated for each candidate are shown.

Options 1, 2 and 4 permit review of the operation as planned for each cut sequence. CPPP's choice of cut sequence can be overridden using Option 3. After the choice of cut sequence is final, the detailed plan for the candidate machine tool is determined.

Interaction Point 12

```
UTRC CPPP SYSTEM. ACCEPT/MODIFY SELECTED MACHINE TOOL
OP   20   DESCRIPTION:  TURN
```



```
          TIME      COST     ID      MACHINE TOOL
        -------   --------   --   ----------------------------
         8.251    $ 149.66   1    B&S NO.4 AUTOMATIC
         8.438    $ 150.00   2    TABER
         9.315    $ 175.00   3    PETERMAN P25

 MACHINE TOOL  1 HAS BEEN CHOSEN FOR LOWEST COST

 TYPE C/R TO ACCEPT CHOICE OR TYPE AN OPTION AND REQUIRED DATA

  1,ID OF MACHINE TOOL (SHOWS SELECTED CUT SEQUENCE)
  2,ID OF MACHINE TOOL (SHOWS MACHINE TOOL DATA - NOT AVAILABLE)
  3,ID OF PREFERRED MACHINE TOOL
  4 (SHOW MORE CANDIDATES)
  5 (SHOW PREVIOUS CANDIDATES)
>1,1
```

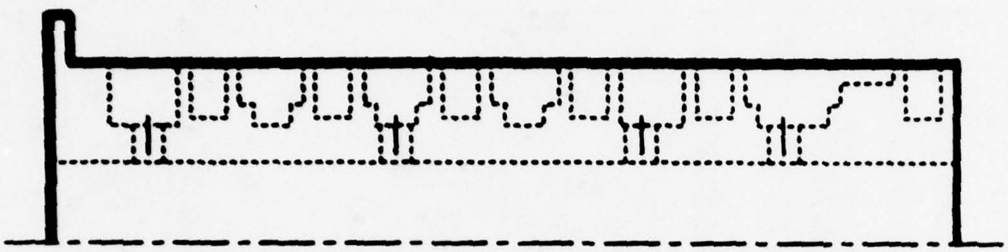
After a plan has been determined for each candidate machine tool, a choice is made on the basis of time or cost. This interaction point displays the data associated with each candidate machine and allows the process planner to override CPPP's choice.

The process planner may use options 1, 4, and 5 to review the plan associated with each candidate machine. Option 3 enables him to change the choice of machine tool. After the machine tool to be used is finalized, a detailed plan for the operation has been established.

Interaction Point 13

UTRC CPPP SYSTEM. ACCEPT/MODIFY DETAILED OPERATION PLAN.

OP 20 DESCRIPTION: TURN
MACHINE TOOL: B&S NO.4 AUTOMATIC



ID	CUT	CUT TYPE	TOOLS	
1	D004	TURN OPN DIA (TO)	1203-001 1205-100	1205-002
2	D006 F005	TURN & FORM (TS)	1203-001 1205-100	1205-002
3	RE80	FACE OPEN (FO)	1203-006 1205-101	1205-004
4	LE01	CUTOFF (CO)	1207-001	

TYPE C/R TO ACCEPT OPERATION PLAN OR TYPE AN OPTION AND REQUIRED DATA:
1 (SHOWS MORE CUTS) 2 (SHOWS PREVIOUS CUTS)
3 (SHOWS MACHINING TOOL DATA) 4,CUT ID (SHOWS MACHINING DATA)
5,NEW OPERATION DESCRIPTION 6,CUT ID, LIST OF NEW TOOLS
7 (REPLACES OPERATION WITH INTERACTION) 8 (TERMINATES PLANNING)
>4,2

This interaction point provides for review and modification of the detailed plan for an operation. All data for the operation can be reviewed. All components of composite cutting tools are listed, rather than just the cutter.

The process planner uses options 1 and 2 to page through the cuts in the operation. The operation description and tooling may be changed. If option 7 is exercised, the detailed plan for the operation is redeveloped using all interaction points (6 through 12). This allows an operation to be replanned with maximum interaction by the process planner.

Interaction Point 14

```
UTRC CPPP SYSTEM.  ACCEPT/MODIFY FINAL PROCESS PLAN DATA.

  TIME     COST OP #          DESCRIPTION                      MACHINE TOOL
------ ------- ---- ------------------------------ --------------------
   .00     .00   10 DRAW MATERIAL                  DRAW MATERIAL BENCH
  6.72  317.92   20 TURN                           B&S NO.4 AUTOMATIC
  1.30   32.50   30 HEAT TREAT PER PMP510          HEAT TREAT FURNACE
  1.88   52.73   40 GRIND LONGEST OD               CINN. C'LESS BAR
  4.92  629.31   50 DRILL THRU BORE                DEHOFF 2 SPINDLE
  2.40  210.00   60 TURN                           L&S PT15
   .42   25.42   70 HAND REAM THRU BORE            BENCH LAP
  2.25  847.24   80 HONE THRU BORE                 MICROMATIC 723
  3.35  168.80   90 GRIND LONGEST OD               B&S NO.5
  1.88  293.24  100 GRIND FREE END                 B&S (8X24)
  9.25  622.00  110 CRUSH GRIND O.SEAL GROOVES     VAN NORMAN 418
  9.08  783.84  120 CRUSH GRIND GROOVES            VAN NORMAN 418
   .00     .00  130 DEBURR PART                    VIBRATORY TUB
   .00     .00  140 STRESS RELIEF PER PMP110       STRESS RELIEF FURN.
   .00     .00  150 MASK NITRIDED SURFACES         MASKING BENCH
   .00     .00  160 COPPER PLATE PART PER PMP210   TANK - COPPER PLATE
   .00     .00  170 UNMASK PART                    TANK - COPPER PLATE
  2.67  847.25  180 HONE THRU BORE                 MICROMATIC 723
   .00     .00  190 NITRIDE PER HS1173 AND PMP505  FURNACE
   .00     .00  200 STRIP COPPER PLATE PER PMP210  TANK - STRIP

 67.82 6099.32      TOTALS      (THERE ARE MORE OPERATIONS)

    TYPE C/R TO ACCEPT SEQUENCE OR TYPE AN OPTION AND REQUIRED DATA
1 (SHOWS MORE OPERATIONS)   2 (SHOWS PREVIOUS OPERATIONS)
3,NOT AVAILABLE
4,NOT AVAILABLE
5,NOT AVAILABLE                    6,OPERATION NUMBER,NEW DESCRIPTION
7,OPERATION NUMBER,NEW MACHINE TOOL
8,OPERATION NUMBER (SHOW OPERATION PLAN)
>
```

The completed process plan can be reviewed and modified at this interaction point. The display gives the description, machine, time, and cost for each operation. The description and machine can be changed. The detailed plan for any operation can be reviewed. A full capability to add, delete, and modify operations could be implemented in the future.

Interaction Point 15

```
UTRC CPPP SYSTEM.  TERMINATE PROCESS PLANNING SESSION

TYPE C/R TO SIGN OFF OR TYPE NUMBER OF SELECTED OPTION
   1 PRODUCE SUMMARY OF OPERATIONS
   2 PRODUCE OPERATION SHEETS
   3 PRODUCE SUMMARY OF OPERATIONS AND OPERATION SHEETS
   4 SAVE PARTIAL/COMPLETED PLAN JUST GENERATED (NOT YET AVAILABLE)
   5 START ANOTHER PROCESS PLANNING SESSION (NOT YET AVAILABLE)
>3
```

A CPPP session is terminated at this interaction point. The process planner can direct that a summary of operations, detailed operation sheets, or both be output. These are produced by a line printer and plotter. At present, the session must end with the user typing RETURN to end his terminal session. Future options could permit saving a partial/complete plan in computer storage and starting a new CPPP session.

APPENDIX C

MANUFACTURING DATA BASE

CPPP requires a large data base containing a variety of manufacturing information. This is a local data base in the sense that its content is determined by the manufacturing practice and environment of a particular workshop. The size of the data base and the frequency with which it will be accessed require that it be efficiently organized and managed.

The current manufacturing data base is divided into six files;

1. Part file
2. Process decision rule file
3. Machine tool file
4. Cut application file
5. Cut parameter file
6. Machinability file

Five of these contain essentially numeric data. The process decision model file contains manufacturing rules rather than numeric data. In addition to the files listed above, there are temporary files created by the CPPP system for use in subsequent processing.

File Content Descriptions

Part File

The part file contains part design and raw material specifications. The design specifications are equivalent to design drawings, giving a full geometric description of the part as well as other information.

The file consists of an index and part descriptions. The index simply lists the part numbers contained in the file, giving the location and length of each part.

A part description is itself a hierarchial data structure that consists of a part header block, surface and feature blocks, and geometric control blocks. The part header block contains general information on the part -- part name and number, part family, classification code, material and material hardness, raw material form, overall part size, latest engineering change and process plan revision number, etc.

Finished part and raw material geometries are specified using data blocks which describe surfaces and features. A surface is a portion of the cylindrical part geometry that can be represented by a canonical geometric form. The CPPP system handles three surface types:

(1) Diameters, described by cylinders whose axes are the cylindrical part's axis of rotation.

(2) Faces, described by planes perpendicular to the part's axis of rotation.

(3) Tapers, described by cones whose axes are the part's axis of rotation.

Feature blocks are used to describe features machined into surfaces. These may be of two types:

(1) The feature is a surface of rotation about the part axis. In this case, if the feature has more than one surface, the feature block serves as a linkage between the parent surface and the surfaces composing the feature. In this class are grooves, recesses, chamfers

(2) The block describes a noncylindrical feature in the basically cylindrical geometry. It may also specify a feature which is geometrically cylindrical, but whose axis is not the part axis (e.g., a radial hole). This type of feature block is used for slots, radial holes, bolt holes, lugs, face windows, threads, and flats.

The individual surface and feature blocks are integrated into a full part geometry description by hierarchical chaining. Primary part surfaces compose the highest level. There is also, for each primary surface, a chain (possibly empty) containing the features machined into that surface. For each multi-surface cylindrical feature, there is further a chain containing the surfaces of the feature. Feature and surface chains continue to alternate in this manner until the lowest level surfaces/features are described. Figure C1 illustrates the chaining mechanism.

The data content of surface and feature blocks is divided into common attributes and particular attributes. Common attributes are relevant to all surfaces/features and appear in all blocks. These give such data as block type, surface/feature name, pointer for chaining, pointer to canonical geometric representation, and governing surface. Particular attributes give information applicable to one or more surface/feature types, but not to all. Particular attributes of a radial hole, for example, include

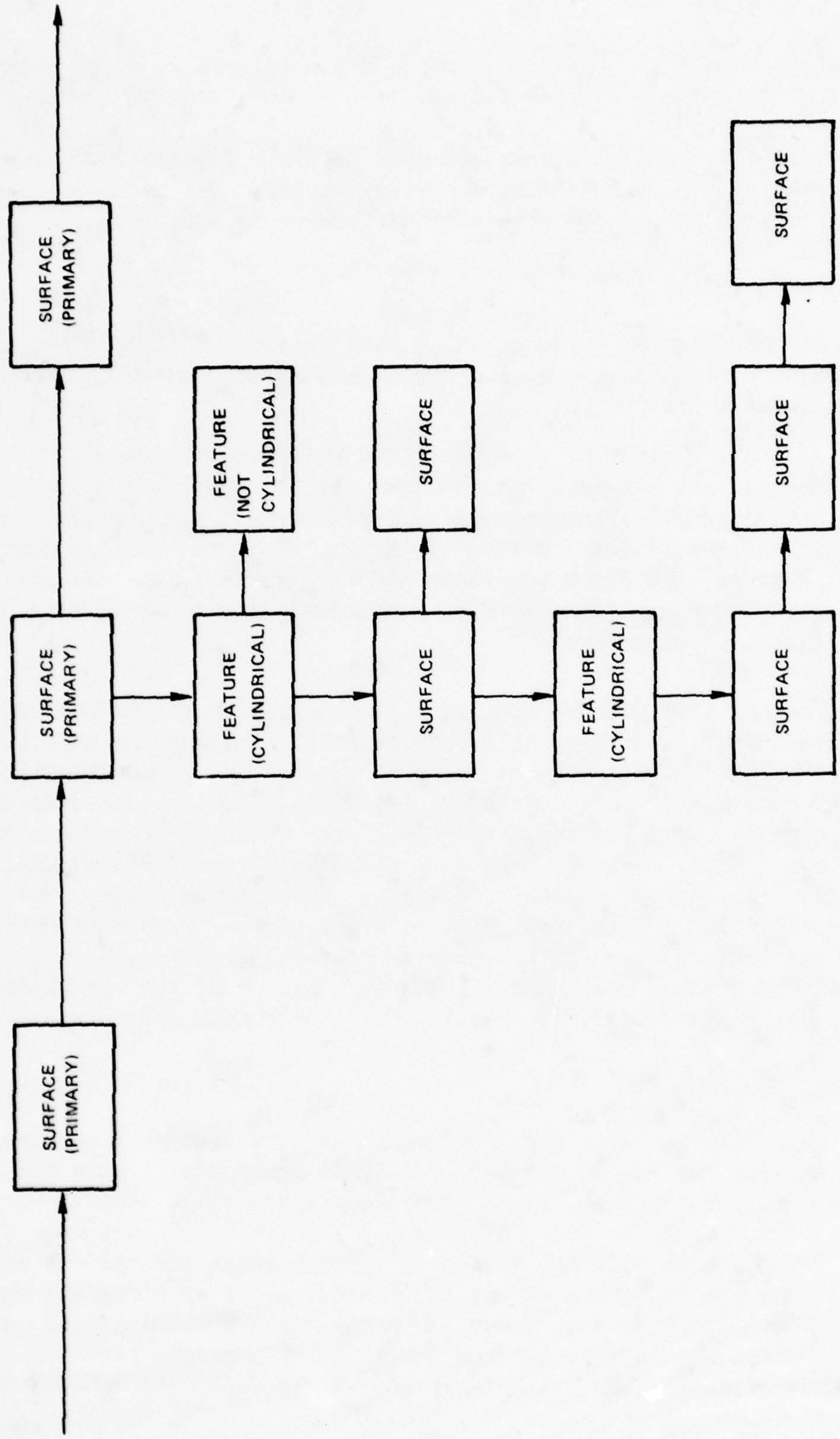


FIGURE C1. CHAINING SCHEME FOR SURFACE AND FEATURE BLOCKS

diameter, diametral tolerance, depth, depth tolerance, drill point angle, point of entry, and surface finish.

Geometric control blocks are used to state geometric constraints such as concentricity, angularity, and straightness. One or more geometric control blocks may be associated with each surface or feature block.

Machine Tool File

The machine tool file contains data on machine classes and machine tools. The machine class data contains the machine class name plus average diametral and lateral stock removal.

The data describing a machine tool consists of general data given for all machines and specific data relevant to the machine's class. The general data includes the machine tool name, number, and location; a number of time and cost related parameters (e.g., operator cost per hour, machine rate, average time for basic setup and additional setup time per tool, average tool change time, average piece load time); and minimum diametral and lateral stock removal.

The specific machine tool data in the file is a function of the machine tool's class. It is present for cylindrical metalcutting machine classes such as lathe, deep hole drill, crush grinder, internal diameter grinder, outside diameter grinder, surface grinder, and hone. This data is used to help select the proper machines. Data for a lathe, for example, includes minimum and maximum part length, maximum chuck diameter, type of control (manual, automatic, or N/C), horsepower, number of spindles, and maximum speed. The number of tool positions, longitudinal stroke, cross stroke, number of feeds, minimum feed and maximum feed are given for the turret, front slide, and rear slide. Drilling depth and maximum drill diameter are given for the turret. Number of feeds, minimum feed, and maximum feed for cutoff are also included.

Cut Application File

This file includes a list of each cut type that each machine tool can make and the tool(s) or type(s) of tool it would use to make the cut. It is organized hierarchically by machine class and machine tool.

Each machine tool has a list of numeric codes for the cut applications it can perform and for each cut application a set of alternate cutting tools or tool types that can be used. An entry in the cutting tool set represents a cutter but may in fact be from one to three separate tool numbers -- such as holder, insert, and chipbreaker for single point lathe tools.

Cut Parameter File

The cut parameter file contains fixed-length data blocks, each of which gives certain machining parameters for a machine class-part material combination, with the blocks in random order.

Each data block contains the following:

1. Machine class

2. Part material

3. Stock removal allowance

4. Tolerance information. Tolerances, both diametral and lateral, are given for the following cases:

   (a) Roughing or semifinish tolerances which are applied when the cut is followed by another cut of the same type (e.g., this turning cut is followed by another turning cut)
   (b) Roughing or semifinish tolerances which are applied when the cut is followed by another of a different type (e.g., turn followed by grind)
   (c) Normally desired finish tolerances
   (d) Tightest practical tolerance the machine can hold.

5. Surface finish

6. Maximum depth of cut for roughing cuts

7. Maximum depth of cut for finish cuts.

Machinability File

The machinability file provides the capability to obtain machining recommendations and a tool life estimate for a given cut. The file is organized hierarchically to facilitate searching for the applicable machinability data:

1. First level: machine class

2. Second level: cut type
   part material description
   hardness range

3. Third level: depth of cut
   recommended tool material
   recommended feed
   estimated tool life per edge

4. Fourth level: part material specification
   recommended speed

As the itemization above shows, provision of the machine class, cut application, part material description, hardness, and depth of cut will determine recommended tool material, recommended feed, and estimated tool life. If the part material specification is also given, recommended speed is determined.

Temporary Files

There are four files into which CPPP stores data which is retrieved for later use:

1. Alternate cut sequence file
2. Alternate machine file
3. Operation detail file
4. Output file

CPPP generally considers more than one sequence of cuts for a machine tool and more than one machine tool for a given operation. This is done by planning the operation for several alternatives, then choosing the most economically desirable one. The alternate cut sequence file is used to store data on the operation and resulting workpiece geometry for different sequences of cuts on the same machine tool. When the best cut sequence for the machine tool is determined, that sequence's data is retrieved and becomes the data for that machine tool. The alternate machine file is used to store data on the operation and the part geometry existing following performance of the operation for each candidate machine. Once the most desirable machine for the operation is chosen, the data associated with that machine is retrieved for use in describing the operation and as the input geometry for the next operation.

The operation detail file is used to store a record of each operation planned. This record consists of the following:

1. Operation data. This includes a number of parameters of the operation such as operation number, operation type, machine tool, setup time and lot machining time and cost.

2. Cut data. Each cut made in the operation is described by giving cut type, stock removed, per piece time, tools, surfaces cut, speed, feed, etc.

3. An end-of-operation workpiece geometry description.

The output file is generated when the entire process plan is completed. This file contains the equivalent of process sheets (routing sheet/summary of operations plus individual operation plans). This data is stored in a form which (i) minimizes the effort necessary to output it using the devices available at a given computer installation and (ii) is amenable to the text-editing mode of process planning.

Procedures for Constructing the Data Base

Each of the five numeric files is generated using punched cards or their equivalent. Each file is built from a card deck containing the entire file, rather than being incrementally built/modified. A stand-alone input program processes each deck. The format and content of each of the input decks is given below.

Part File

The input deck for the part file is a sequence of individual part descriptions. Each description consists of (1) a header card giving the part's file retrieval name, whether the part is NEW or OLD to the file, and current file size, (2) three cards giving general part data, (3) a number of cards describing finished part geometry, and (4) a number of cards giving raw material geometry. There is also a separator card which divides the two geometric descriptions. Table C1 gives the format of the general part data cards.

TABLE C1. FORMAT OF GENERAL PART DATA CARDS

	Column(s)	Form*	Data
First card	1-20	A	part number
	21-40	A	part name
	41-48	A	part code
	49-56	A	engineering change number
	57-60	A	revision number
	61-68	A	area
	69-80	A	model
Second card	1-8	R	maximum outer diameter
	9-16	R	minimum internal diameter
	17-24	R	part length
	25-36	A	material type
	37-48	A	material specification
	49	I	hardness type code (1 if Rockwell C, 2 if thousands of PSI)
	50-53	I	raw material hardness - low limit
	54-57	I	raw material hardness - high limit
	58-61	I	finished hardness - low limit
	62-65	I	finished hardness - high limit
	66	I	code number for raw material form (1 for bar stock, 2 for forging, 3 for casting)
	67-74	R	bar diameter (if bar stock)
Third card	1-16	A	forging or casting number
	19-24	R	surface treatment thickness
	25-30	R	surface treatment thickness tolerance
	32-33 35-36 38-39 41-42 44-45 47-48	I	Up to 6 code numbers for blueprint notes applicable to the entire part

*R indicates a real (decimal) number, I an integer, A an alphanumeric string.

Finished part geometry is input using cards which describe each surface and feature of the part. One or more pairs of cards is used for each surface or feature. The surface/feature descriptions are given in clockwise order. If there is no through hole, the surface making the left intersection with the centerline is given first and the surface making the right intersection last. If there is a through hole, the left end is first and the internal surface (internal diameter or countersink) that intersects the left end is last Figure C2). Feature cards are placed after the cards describing the surface into

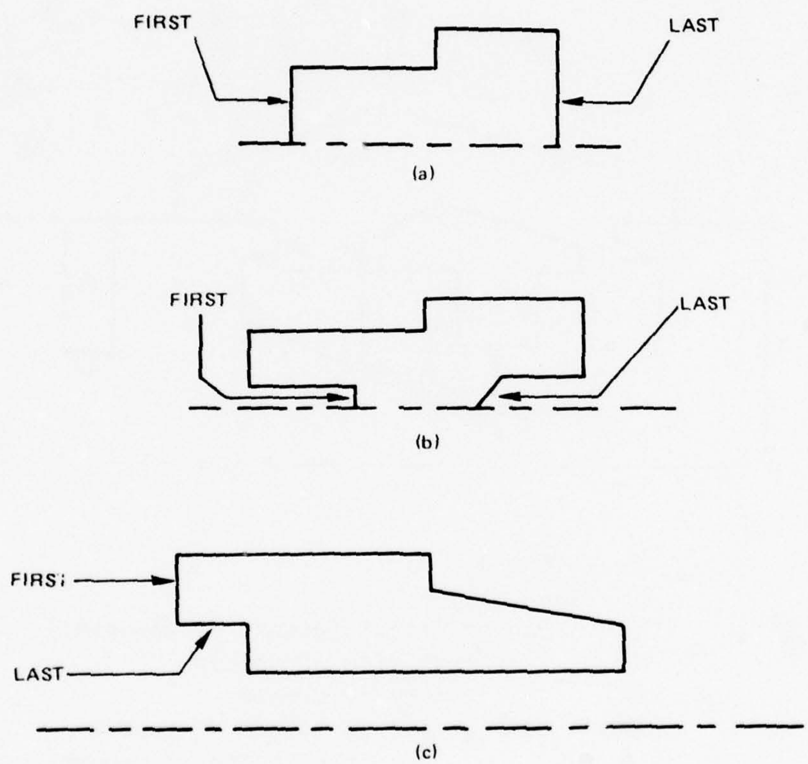
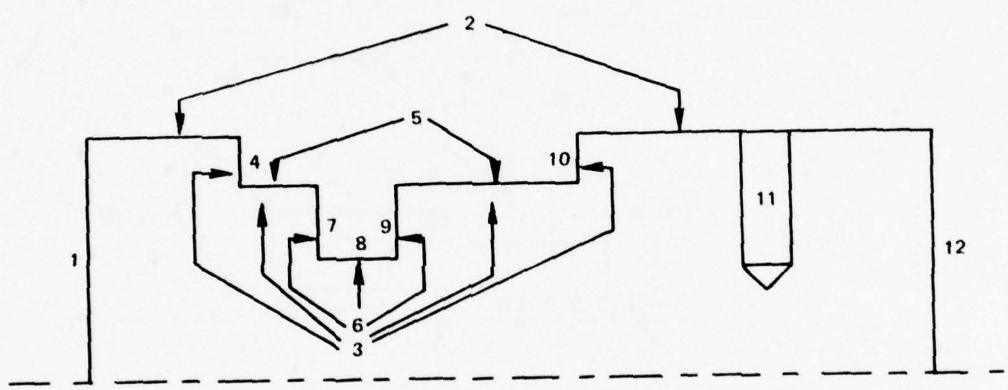


FIGURE C2. ORDER OF SURFACES IN GEOMETRIC DESCRIPTIONS. In (a), the left end would be the first surface given and the right end the last. In (b), the drill points of the left and right internal holes would be the first and last surfaces, respectively. Since the part in (c) has a through hole, the left end is given first and the internal surface intersecting it is last.

which the feature is machined. A relief groove or recess is an exception to this and will precede its parent diameter when at the leading end of the diameter. If a surface has more than one feature, its features are given in a clockwise order. If the feature is multi-surface, cards describing its component surfaces in clockwise order are placed after the feature's card(s). The normal order in which surface/feature descriptions are placed is illustrated in Figure C3.



01 left end
02 diameter
03 recess (first feature of diameter)
04 left side of recess
05 bottom of recess
06 groove in bottom of recess
07 left side of groove
08 bottom of groove
09 right side of groove
10 right side of recess
11 radial hole (second feature of diameter)
12 right end

FIGURE C3. ORDER OF INPUT FOR SURFACES AND FEATURES IN GEOMETRY DESCRIPTION

Each surface or feature description requires one or more pairs of cards. The second card in each pair may be omitted if none of the data on it is relevant. The general form of the pair of cards is shown in Table C2. Table C3 gives certain codes used in those cards. The relevance and/or interpretation of some entries may depend on the type of surface/feature being described.

Surfaces and features fall into four categories:

1. Surfaces have type numbers of the form 0XX. Geometrically, they are cylinders or cones having the part axis as axis of rotation or are planes perpendicular to the part axis. The input card pair describes this rotational geometry.

2. Multisurface rotational features that have the part axis as axis of rotation and that are expanded into surfaces. These have type numbers of the form 1XX. The input card pair for such a surface contains only the feature type. (There is one exception to this rule. For a groove or recess, other than a relief, the beginning corner break is described, and for every groove and recess the identification number of the parent diameter must be given.) This card pair serves to indicate that the following surface card pair describes the first surface of the feature.

3. Rotational features with axis other than the part axis. Type numbers have the form 2XX. The card pair is used to describe the feature's geometry.

4. Nonrotational features. These have type numbers of the form 3XX. The card pair contains only the type number. It indicates the presence of the feature and, by position, the surface into which the feature is machined. There is no geometric description.

Surface/feature identification numbers are assigned sequentially to surfaces and features. Figure C3 illustrates the numbering scheme.

TABLE C2. FORMAT FOR SURFACE/FEATURE CARD PAIR

	Column(s)	Form	Data
First card	1-2	I	surface identification number
	4-6	I	surface/feature type (see Table C3)
	8-15	R	diameter
	17-22	R	diametral tolerance
	24-31	R	lateral dimension
	33-38	R	lateral tolerance
	40-41	I	identification number of reference datum surface. For grooves, recesses and reliefs use ID number of parent diameter
	43-50	R	nominal lateral position
	52-57	R	angle or intersection radius
	59-64	R	angular or radial tolerance
	66	I	angle/intersection code (see Table C3)
	68-70	I	surface finish
	72	I	window type or shape code (see Table C3)
Second Card	8-9	I	geometric control type (see Table C3)
	11-18	R	geometric control tolerance
	20-21	I	identification number of reference surface for geometric control
	26-31	R	surface treatment thickness
	33-38	R	surface treatment thickness tolerance
	40-46	R	radial or bolt hole depth
	48-53	R	radial or bolt hole tolerance
	55-56	I	identification number of surface-thru-to for hole
	58	I	O-seal groove flag (1 if o-seal, 0 otherwise)
	60-61	I	up to 3 code numbers for blueprint notes applicable to this surface
	63-64	I	
	66-67	I	
	69-74	R	angle of radial or bolt hole

TABLE C3. CODE NUMBERS USED IN SURFACE/FEATURE CARDS.

Surface/feature types

001	diameter
002	face (not an end)
003	left or right end
004	taper
005	chamfer
006	centerdrill (for turning center)
007	drill point
008	countersink (for turning center)
009	countersink (not for turning center)
100	groove
101	recess
102	relief
103	half fin
200	radial hole
201	bolt hole
300	axial slot, round bottom
301	axial slot, square bottom
302	lug
303	flat
304	window
305	thread
306	cross slot, round bottom
307	cross slot, square bottom
308	tab
309	scallop

Angle/intersection codes

1	angle
2	fillet
3	corner break (in this case the minimum and maximum radii are given by fields 52-57 and 59-64).
4	left fillet radius and tolerance, slots only
5	right fillet radius and tolerance, slots only
6	bore edge break and tolerance, radial holes and windows

Geometric control types

01	timing feature reference
02	concentricity
03	straightness
04	roundness
05	angularity
06	true position

Window type or shape code

1	face window with curved top and bottom
2	face window with straight top and bottom
3	irregular window in OD thru to ID
4	regular window in OD thru to ID

Following are notes on the relevance and interpretation, for each surface type, of the fields of the surface cards.

1. Diameter. Fill diameter fields, omitting lateral fields. Give fillet or corner break rather than angle. Fill in surface finish. Give geometric control and blueprint note codes if present.

2. Face or end. Complete lateral fields, omitting diameter fields. Give fillet or corner break rather than angle. Give surface finish. Other fields are completed if needed.

3. Taper. A taper is described using one of three methods. Each method requires two card pairs with the same surface identification number.

   a. Gauge diameter method. On the first card pair give diameter (but not diametral tolerance), all lateral fields, and surface finish. The angle and angular tolerance fields are used to describe the angle of the taper. Complete geometric control and blueprint note fields as needed. On the second card pair enter intersection fields.

   b. Gauge dimension method. On the first card pair fill both diameter fields, lateral dimension (but not tolerance), datum surface, nominal lateral position, angle and tolerance, and surface fields. Give geometric control and blueprint notes as needed. On the second pair enter intersection data.

   c. Two point method. Each card pair is devoted to a point. Fill in diametral and lateral fields on each, except that either diametral tolerance is left blank on both card pairs or lateral tolerance is left blank on both card pairs. The first pair is used to give intersection and surface finish and, if needed, geometric control and blueprint notes.

4. Chamfer and countersink. Two card pairs having the same surface number are used. On the first, two of the following three sets of fields must be given: (i) diametral fields, giving the intersection with the adjacent face, (ii) lateral fields, giving the intersection with the adjacent diameter, (iii) angle fields, giving the angle of the chamfer. Enter surface finish and, if needed, geometric control and blueprint notes. On the second, fill the intersection fields.

5. Centerdrill. The same data is given as for a diameter. There must be a turning countersink between the centerdrill and the adjacent part end.

6. Drill point. The end or bottom of the smallest diameter blind hole in each end must be a drill point. The ends of larger blind holes may be described as drill points provided they are not vertical. Two card pairs are usually used. On the first, give all lateral fields, angle fields (to describe the drill point angle), and surface treatment. On the second, having the same surface number, enter only intersection fields. This second pair is not used if the drill point is the final surface given for the part; i.e., the smallest hole in the right end when there is no through hole.

7. Radial hole. Diameter fields give the size of the hole, lateral fields locate the hole's centerline, angle fields are used to give drillpoint angle and tolerance, and the geometric control surface gives the surface-through-to, if any. Surface finish is given, as are blueprint notes present. On the second card of the pair the hole depth and tolerance are given in columns 40-46 and 48-53.

8. Bolt hole. Data given is the same as for a radial hole, except that lateral dimension and tolerance are used to give the centerline's diameter and diametral tolerance.

Raw material geometry is described by surface/feature card pairs in the same manner as the finished part geometry. (Of course, there will generally be fewer surfaces and features to describe.) The order in which surfaces/features are input is determined by applying to the raw material geometry the same rules given above for the finished geometry. Surface/feature identification numbers are identical in the raw material geometry description to what they were in the finish geometry, with missing items omitted (See Figure C4). The datum plane used for lateral positions in the raw material description may, if desired, differ from that used in the finished geometry description. The correlation between the two is input on a card which is placed between the two geometric descriptions. This card must be included even if the same origin is used for both geometry descriptions -- it serves as a separator. Table C4 gives the format of this card.

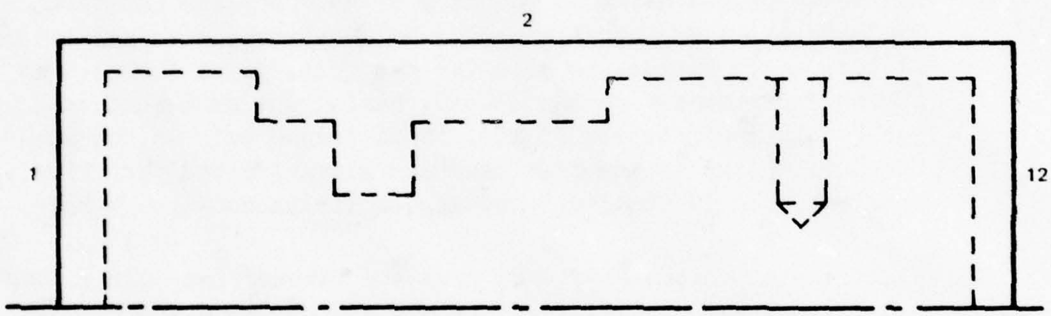


FIGURE C4. NUMBERING SCHEME FOR RAW MATERIAL GEOMETRY. The ends of the blank are associated with the ends of the part, and the diameter of the blank with the maximum part diameter (see Figure C3).

TABLE C4. FORMAT OF GEOMETRY SEPARATOR CARD.

Column(s)	Form	Data
4-6	I	"999"
24-31	R	The lateral position, according to the datum used in the raw material description, of the datum plane of the finished geometry.

Machine Tool File

Four card types are used to construct the machine tool file:

1. Machine class card
2. Machine tool card
3. Common machine tool data card for data relevant to machine tools of all classes
4. Particular machine tool data cards for data specific to machine tools of a particular class. As many as four such cards may be required for a machine tool.

The input deck is built from these cards in the following manner:

```
Machine class card for first class
     Machine tool card for machine in first class
          Common data card for that machine
          Particular data card(s) for that machine (if any)
     Machine tool card for another machine in first class
          Common data card
          Particular data card(s)
                    •
                    •
                    •
Machine class card for second class
     Machine tool card for machine in second class
          Common data card
          Particular data card(s)
                    •
                    •
                    •
```

Tables C5, C6, and C7 give formats for the machine class card, machine tool card, and common machine tool data card. Particular data cards for each allowable type of machine tool are given in Tables C8 through C14.

TABLE C5. MACHINE CLASS CARD FORMAT

Column(s)	Form	Data
1	A	"C"
4-23	A	machine class name
26-29	I	machine class code number (user determined)
32-36	I	average diametral stock removal in units of 1/100,000 inch
39-43	I	average lateral stock removal in units of 1/100,000 inch
46-47	I	machine class type (see list below)

The machine class type cues the processor on the specific data to be provided for subsequent machine tools. There are nine acceptable codes:

-1	not a metal cutting machine class; no specific data present
0	a non-cylindrical metal cutting class; no specific data provided
1	lathe
2	deep hole drill
3	crush grinder
4	internal diameter grinder
5	external diameter grinder
6	surface grinder
7	hone

TABLE C6. MACHINE TOOL CARD FORMAT

Column(s)	Form	Data
1	A	"M"
4-23	A	machine tool name
26-29	I	machine tool code number (user determined)

TABLE C7. COMMON MACHINE TOOL DATA CARD FORMAT

Column(s)	Form	Data
1	A	"G"
4-9	A	shop's machine code
11-14	A	location (shop, shop area, or other)
16-21	R	operator cost (dollars per hour)
22-27	R	machine cost (dollars per hour)
28-33	R	average setup cost (dollars)
34-39	R	average time for basic setup (minutes)
40-45	R	average added setup time per tool (minutes)
46-51	R	average tool change time (minutes)
52-57	R	average workpiece load time (minutes)
58-63	R	turret index time (minutes)
64-69	R	minimum diametral stock removal (inches)
70-75	R	minimum lateral stock removal (inches)
77	I	machine rate

TABLE C8. FORMAT OF PARTICULAR MACHINE TOOL DATA CARD FOR LATHES

Card	Column(s)	Form	Data
1	1	A	"1"
	2-8	R	maximum part length (inches)
	9-16	R	minimum part length (inches)
	17-24	R	maximum part diameter (inches)
	25-32	R	minimum part diameter (inches)
	33-40	R	maximum chuck diameter (inches)
	41-48	R	maximum part length/diameter ratio
	49-56	R	minimum part length/diameter ratio
	57-64	I	control type (1 for manual, 2 for automatic, 3 for numerical control, 4 for other)
	65-72	R	horsepower
	73-80	I	number of spindles
2	1	A	"2"
	2-8	R	maximum speed (RPM)
	9-16	I	turret--number of tool positions
	17-24	R	drill depth (inches)
	25-32	R	maximum drill diameter (inches)
	33-40	R	longitudinal stroke (inches)
	41-48	R	cross stroke (inches)
	49-56	R	radial clearance (inches)
	57-64	I	number of feeds
	65-72	R	maximum feed (IPR)
	73-80	R	minimum feed (IPR)
3	1	A	"3"
	2-8	I	front slide--number of tool positions
	9-16	R	longitudinal stroke (inches)
	17-24	R	cross stroke (inches)
	25-32	I	number of feeds
	33-40	R	maximum feed (IPR)
	41-48	R	minimum feed (IPR)
	49-56	I	rear slide--number of tool positions
	57-64	R	longitudinal stroke (inches)
	65-72	R	cross stroke (inches)
	73-80	I	number of feeds
4	1	A	"4"
	2-8	R	rear slide--maximum feed (IPR)
	9-16	R	minimum feed (IPR)
	17-24	I	cutoff--number of feeds
	25-32	R	maximum feed (IPR)
	33-40	R	minimum feed (IPR)

TABLE C9. FORMAT OF PARTICULAR MACHINE TOOL DATA CARD FOR DEEP HOLE DRILLS

Card	Column(s)	Form	Data
1	1	A	"1"
	2-8	R	maximum hole diameter (inches)
	9-16	R	minimum hole diameter (inches)
	17-24	R	maximum hole length (inches)
	25-32	R	maximum part length (inches)
	33-40	R	maximum part diameter (inches)
	41-48	I	control type
	49-56	R	horsepower
	57-64	I	number of spindles
	65-72	R	maximum speed (RPM)
	73-80	R	maximum feed (IPR)

TABLE C10. FORMAT OF PARTICULAR MACHINE TOOL DATA CARDS FOR CRUSH GRINDERS

Card	Column(s)	Form	Data
1	1	A	"1"
	2-8	R	maximum form depth (inches)
	9-16	R	maximum form width (inches)
	17-24	R	maximum part length (inches)
	25-32	R	maximum part diameter (inches)
	33-40	I	center/centerless (1 or 2)
	41-48	I	control type
	49-56	R	horsepower
	57-64	R	maximum part speed (RPM)
	65-72	R	minimum part speed (RPM)
	73-80	R	maximum in-feed (IPR)
2	1	A	"2"
	2-8	R	maximum wheel diameter (inches)
	9-16	R	minimum wheel diameter (inches)
	17-24	R	maximum wheel width (inches)
	25-32	R	minimum wheel width (inches)
	33-40	R	wheel hole diameter (inches)

TABLE C11. FORMAT OF PARTICULAR MACHINE TOOL DATA CARDS FOR INTERNAL DIAMETER GRINDERS

Card	Column(s)	Form	Data
1	1	A	"1"
	2-8	R	maximum hole diameter (inches)
	9-16	R	minimum hole diameter (inches)
	17-24	R	maximum hole length (inches)
	25-32	R	maximum part length (inches)
	33-40	R	maximum part diameter (inches)
	41-48	R	faceplate diameter (inches)
	49-56	I	control type
	57-64	R	horsepower
	65-72	R	maximum part speed (RPM)
	73-80	R	minimum part speed (RPM)
2	1	A	"2"
	2-8	R	maximum in-feed (IPR)

TABLE C12. FORMAT OF PARTICULAR MACHINE TOOL DATA CARDS FOR EXTERNAL DIAMETER GRINDERS

Card	Column(s)	Form	Data
1	1	A	"1"
	2-8	R	maximum part diamter (inches)
	9-16	R	minimum part diameter (inches)
	17-24	R	maximum part length (inches)
	25-32	I	center/centerless (1 or 2)
	33-40	I	control type
	41-48	R	horsepower
	49-56	R	maximum part speed (RPM)
	57-64	R	maximum feed (IPR)
	65-72	R	maximum wheel diameter (inches)
	73-80	R	maximum wheel width (inches)
2	1	A	"2"
	2-8	R	minimum wheel width (inches)
	9-16	R	wheel hole diameter (inches)

TABLE C13. FORMAT OF PARTICULAR MACHINE TOOL DATA CARDS FOR SURFACE GRINDERS

Card	Column(s)	Form	Data
1	1	A	"1"
	2-8	R	maximum part length (inches)
	9-16	R	maximum part width (inches)
	17-24	R	maximum part height (inches)
	25-32	R	maximum grind length (inches)
	33-40	R	maximum grind width (inches)
	41-48	I	control type
	49-56	R	horsepower
	57-64	R	maximum speed (RPM)
	65-72	R	maximum feed (IPR)
	73-80	R	wheel diameter (inches)
2	1	A	"2"
	2-8	R	wheel width (inches)
	9-16	R	wheel hole diameter (inches)

TABLE C14. FORMAT OF PARTICULAR MACHINE TOOL DATA CARD FOR HONES

Card	Column(s)	Form	Data
1	1	A	"1"
	2-8	R	maximum hole diameter (inches)
	9-16	R	minimum hole diameter (inches)
	17-24	R	maximum part length (inches)
	25-32	R	horsepower
	33-40	I	number of spindles
	41-48	R	maximum speed (RPM)
	49-56	R	minimum speed (RPM)
	57-64	R	maximum stroke (inches)
	65-72	I	control type

Cut Application File

The input deck for the cut application file consists of seven types of cards:

1. Machine class card
2. Machine tool card
3. Part family card
4. Directory header card
5. Directory data card
6. Tooling header card
7. Tooling data card.

The input deck is built from these cards in the following manner:

```
Machine class card for first class
     Machine tool card for first machine in class
          Part family card of first family for machine
                    .
                    .
          Part family card of last family for machine
     Machine tool card for second machine in class
                    .
                    .
Machine class card for next class
                    .
                    .
          Part family card of last family for last machine in last class
Directory header card for first directory
     Directory data card(s) -- as many as needed
Directory header card for second directory
                    .
                    .
     Directory header card for last directory
          Directory data card(s)
     Tooling header card for first directory
          Tooling data cards -- as many blocks of 50 as needed
                    .
                    .
     Tooling header card for last directory
          Tooling data cards
```

Each part family card must reference a directory, although several can reference the same one. Each directory header card must reference a unique tooling header card. (The tooling header cards do not actually have to occur in the same order as the directories, contrary to what may be suggested in the deck setup example.)

The complex organization of this file is a result of the flexibility designed into it. In particular, it is possible to designate different tools for the same cut if the parts come from different families; however, this is not done in the demonstration.

Tables C15 through C20 specify the formats of all cards except the tooling data card.

TABLE C15. FORMAT OF MACHINE CLASS CARD FOR CUT APPLICATION FILE

Column(s)	Form	Data
1	A	"C"
4-23	A	machine class name*
26-29	I	machine class code*

*must be identical to entry in machine tool file

TABLE C16. FORMAT OF MACHINE TOOL CARD FOR CUT APPLICATION FILE

Column(s)	Form	Data
1	A	"M"
4-23	A	machine tool name*
26-29	I	machine tool code*

*must be identical to entry in machine tool file

TABLE C17. FORMAT OF PART FAMILY CARD FOR CUT APPLICATION FILE

Column(s)	Form	Data
1	A	"F"
4-9	A	family code (same as in part file)
16-21	A	directory name (same as on some following directory header card)

TABLE C18. FORMAT OF DIRECTORY HEADER CARD FOR CUT APPLICATION FILE

Column(s)	Form	Data
1	A	"D"
4-9	A	directory name (same as on one or more part family cards)
16-21	A	tooling data name (same as on some following tooling header card)
26-29	I	number of pairs of items to follow on directory data card(s)

TABLE C19. FORMAT OF DIRECTORY DATA CARD FOR CUT APPLICATION FILE

Column(s)	Form	Data
2-8	I	cut application code
9-16	I	word number in tooling data at which tool list for above cut application starts
10-24	I	cut application code
25-32	I	tool list start
33-40	I	cut application code
41-48	I	tool list start
49-56	I	cut application code
57-64	I	tool list start
65-72	I	cut application code
73-80	I	tool list start

TABLE C20. FORMAT OF TOOLING HEADER CARD FOR CUT APPLICATION FILE

Column(s)	Form	Data
1	A	"A"
4-9	A	tooling data name (same as on one preceding directory header card)
26-29	I	number of blocks of tooling data cards immediately following

The tooling data cards contain a computer-readable representation of the tooling lists for the cut applications and are grouped together in blocks that represent 300 words of computer storage. For this reason it is rather difficult to manually prepare these cards, and a computer program has been provided for that purpose. This program punches out both the tooling data cards and the directory data cards. The input format for this program is given in Table C21.

TABLE C21. FORMAT OF INPUT CARDS FOR TOOLING DATA

Column(s)	Form	Data
1-12	A	cut application name
14	A	"X" if next application is same as this
16-21	A	tool list key (see below)
23-28	A	tool name
40-55	A	tool name
57-62	A	tool name
79-80	I	cut application code

Each entry in the tooling data list is a set of one, two, or three items, and each item may be an actual tool number or a tool type. If there are more than one item, only one can actually be a cutting tool and the other(s) must be auxiliary tools. If there is only one item it must be in columns 23-28, and if there are two they must be in columns 23-28 and 40-55. The tool list key (columns 16-21) tells how many items are present and what they are. The key is composed of three two-digit subkeys corresponding to the three possible tool names. TABLE C22 gives the possible values for each two-digit subkey.

TABLE C22. SUBKEY VALUES FOR TOOL LIST KEY IN TOOLING INPUT DATA FOR CUT APPLICATION FILE

Subkey	Corresponding tool name
00	(blank-no tool)
01	holder tool number
02	holder tool type
03	insert tool number
04	insert tool type
05	chipbreaker tool number
06	chipbreaker tool type
07	cutter tool number
08	cutter tool type
09	head number
10	grinding wheel number
11	grinding wheel type
12	drill number
13	drill type
14	reamer number
15	reamer type
16	lap number
17	lap type
18	honing mandrel number
19	honing mandrel type
20	honing stone number
21	honing stone type
22	adapter number
23	adapter type
24	regulating wheel number
25	regulating wheel type
26	electrode number
27	electrode type

Cut Parameter File

The input deck for the cut parameter file consists of three types of cards:

1. Machine class card
2. Material card
3. Cut parameter data card

The input deck is formed as follows. The first card is a machine class card. This is followed by several pairs of cards, each consisting of a material card followed by a data card. Each pair gives cut parameter data for the machine class - material combination. The second, third, etc., machine classes are handled in the same way:

```
Machine Class card
   Material card
     Data card
   Material card
     Data card
     .
     .
     .
Machine class card
   Material card
     Data card
     .
     .
     .
```

Tables C23, C24 and C25 give formats for each of these cards.

TABLE C23. FORMAT OF MACHINE CLASS CARD FOR CUT PARAMETER FILE

Column(s)	Form	Data
1	A	"C"
4-23	A	machine class name
25-28	I	machine class code number
30-33	I	number of material/data card pairs to follow

TABLE C24. FORMAT OF MATERIAL CARD FOR CUT PARAMETER FILE

Column(s)	Form	Data
1	A	"M"
4-15	A	material description

TABLE C25. FORMAT OF CUT PARAMETER DATA CARD

Column(s)	Form	Data
4-9	R	depth of stock removed
10-15	R	roughing tolerance, same type, diametral
16-21	R	roughing tolerance, same type, lateral
22-27	R	roughing tolerance, different type, diametral
28-33	R	roughing tolerance, different type, lateral
34-39	R	finish tolerance, diametral
40-45	R	finish tolerance, lateral
46-51	R	tighest tolerance, diametral
52-57	R	tighest tolerance, lateral
58-63	R	surface finish
64-69	R	maximum depth, rough cuts
70-75	R	maximum depth, finish cuts

Machinability File

The machinability file is constructed from four card types:

1. Machine class card
2. Cut application/material card
3. Depth of cut card
4. Material specification card

The input deck is constructed hierarchically:

Machine class card
    Cut application/material card
        Depth of cut card
            One or more material specification cards
            .
            .
            .
    Cut application/material card
    .
    .
    .
Machine class card
.
.
.

Tables C26 through C29 give formats for these cards

TABLE C26. FORMAT OF MACHINE CLASS CARD FOR MACHINABILITY FILE

Column(s)	Form	Data
1	A	"C"
4-23	A	machine class name
25-29	I	machine class code number
31-34	I	number of cut application/material cards to follow

TABLE C27. FORMAT OF CUT APPLICATION/MATERIAL CARD FOR MACHINABILITY FILE

Column(s)	Form	Data
1	A	"T"
4-7	I	cut application code number
9-20	A	part material description
22-25	I	low limit of part hardness
27-30	I	high limit of part hardness
32-35	I	number of depth of cut cards to follow

TABLE C28. FORMAT FOR DEPTH OF CUT CARD IN MACHINABILITY FILE

Column(s)	Form	Data
1	A	"D"
4-9	R	depth of cut (inches)
11-22	A	recommended tool material
24-29	R	Recommended feed (IRP)
31-36	R	estimated tool life per edge (minutes)
38-41	I	number of material specification cards to follow

TABLE C29. FORMAT OF MATERIAL SPECIFICATION CARD IN MACHINABILITY FILE

Column(s)	Form	Data
1	A	"S"
52-63	A	material specification
65-70	R	recommended speed (SFPM)

APPENDIX D

COMPUTER PROCESS PLANNING LANGUAGE AND LANGUAGE PROCESSOR

A special purpose Computer Processing Planning Language (COPPL) has been developed to express process decision models. The language is English in form and its vocabulary consists of common words and manufacturing terms. Models written in COPPL are readable with little training or experience. Therefore, models also serve to directly document the manufacturing rationale of a workshop.

A language processor converts the process planning language into a more efficient computer readable code. The COPPL language could be interpreted directly, but that approach would be less efficient. There are three steps in converting process models written in COPPL: lexical analysis, syntactical analysis, and code generation. The lexical analysis reads the input language constructs and decomposes the character sets into words and symbols known to the language processor. The syntactical analysis determines the structure of the language constructs so that the grammatical meaning is known. The final code generation step produces the code that is stored in the CPPP data base.

The first two steps of lexical and syntactical analysis combine to provide the basic language translation function. This function reads the programmed elements of a process model and through a "syntax-directed" parsing procedure determines the type of elements and their grammatical structure. For example, Figure D1 shows an example of a programmed element that might appear in a process model. The language translation would recognize this as a "simple metalcutting axiom" consisting of the structure in Table D1.

```
Turn outside surface on MC0400 (Automatic Bar) in normal if

        Surface is an open diameter (or)

        Surface is a semiopen diameter,
           surface is exposed (or)

        Surface is an end $
```

FIGURE D1. EXAMPLE OF A PROCESS MODEL PROGRAMMED ELEMENT

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AD-A055 893 UNITED TECHNOLOGIES RESEARCH CENTER EAST HARTFORD CONN F/G 5/3

COMPUTERIZED PRODUCTION PROCESS PLANNING.(U)

NOV 77 W S MANN, M S DUNN, S J PFLEDERER DAAK40-76-C-1104

UNCLASSIFIED UTRC/R77-942625-14 NL

3 OF 4

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TABLE D1. EXAMPLE OF METALCUTTING AXIOM STRUCTURE

Structural Elements	Parsed Language
Type of operation	turning
Part surface reference	outside surfaces
Machine reference	MC0400
Part orientation	normal
Conditional expression	A + (B•C) + D

The conditional expression has the form of a boolean equation. In this example, a surface must be an "open diameter" (A) or a "semiopen diameter" (B) that is "exposed" (C) or a part "end" (D). All programmed elements of a process model have a similar structure.

There are six basic elements, called axioms, that can be used in formulating a process model. They are: simple metalcutting axiom, multiple operation metalcutting axiom, single feature metalcutting axiom, non-metalcutting axiom, branching or transfer axiom and orientation axiom. Examples of all but the last axiom are provided in Section 2.2.

The construction of axioms is governed by the syntax rules that have been developed for the COPPL language. These same rules are used by the language translator to parse programmed statements of a process model. A formal specification of the COPPL language is given in Table D2, using the Backus Normal Form (BNF) for language definition. By this method, each language element or construction is defined in terms of lower level constructions until a primitive level of elements is reached. The BNF definition is of the following form:

A := <X>|<Y>|<X><Y>

The definition is read as ... A is defined to be an X, or a Y, or an X followed by a Y.

BNF language definition generally depends heavily on recursive definition in which a construction is defined in terms of itself. An example of this form is:

A := <X>|<Y><A>

This definition defines A to be an X or any number of Y's followed by an X.

COMPUTER PROCESS PLANNING LANGUAGE (COPPL) DEFINITION

```
PROCESS DECISION MODEL := <PROCESS RULE><END RULE> 1 <PROCESS RULE><PROCESS
          <DECISION MODEL> 1 <TRANSFER RULE><PROCESS DECISION MODEL> 1
          <ORIENTATION RULE><PROCESS DECISION MODEL>
```

RULE CONSTRUCTION

```
PROCESS RULE := <NON-METALCUTTING PROCESS RULE> 1 <SIMPLE METALCUTTING PROCESS
          RULE> 1 <SINGLE FEATURE METALCUTTING PROCESS RULE> 1 <MULTIPLE
          OPERATION METALCUTTING PROCESS RULE>

NON-METALCUTTING PROCESS RULE := <RULE NUMBER><NON-METALCUTTING STATEMENT> 1
          <RULE NUMBER><NON-METALCUTTING STATEMENT><'IF'><CONDITIONAL
          STATEMENT PARAGRAPH>

SIMPLE METALCUTTING PROCESS RULE :=<RULE NUMBER><SIMPLE METALCUTTING
          STATEMENT><'IF'><CONDITIONAL STATEMENT PARAGRAPH> 1 <RULE NUMBER>
          <SIMPLE METALCUTTING STATEMENT><'IF'><CONDITIONAL STATEMENT
          PARAGRAPH><CONTINUED RULE NUMBER><CONTINUED METALCUTTING
          STATEMENT><'IF'><CONDITIONAL STATEMENT PARAGRAPH>

SINGLE FEATURE METALCUTTING PROCESS RULE := <RULE NUMBER><SINGLE FEATURE
          METALCUTTING STATEMENT> 1 <RULE NUMBER><SINGLE FEATURE
          METALCUTTING STATEMENT><'IF'><CONDITIONAL STATEMENT PARAGRAPH>

MULTIPLE OPERATION METALCUTTING PROCESS RULE := <RULE NUMBER><MULTIPLE
          OPERATION METALCUTTING STATEMENT><'IF'><CONDITIONAL STATEMENT
          PARAGRAPH>

ORIENTATION RULE := <RULE NUMBER><ORIENTATION STATEMENT>

TRANSFER RULE := <RULE NUMBER><TRANSFER STATEMENT>

END RULE := <RULE NUMBER><END STATEMENT>
```

TABLE D2. COMPUTER PROCESS PLANNING LANGUAGE (COPPL) DEFINITION (Continued)

CONSTRUCTIONS ABOVE STATEMENT LEVEL

```
CONDITIONAL STATEMENT PARAGRAPH := <LOGICAL EXPRESSION> 1 <LOGICAL EXPRESSION>
         <'(AND)'><PROVISO EXPRESSION>

LOGICAL EXPRESSION := <LOGICAL EXPRESSION TERM> 1 <LOGICAL EXPRESSION><'(OR)'>
         <LOGICAL EXPRESSION TERM>

LOGICAL EXPRESSION TERM := <FEATURE CONDITIONAL STATEMENT> 1 <ATTRIBUTE
         CONDITIONAL STATEMENT> 1 <LOGICAL EXPRESSION TERM><,><LOGICAL
         EXPRESSION TERM>

PROVISO EXPRESSION := <PROVISO EXPRESSION TERM> 1 <PROVISO EXPRESSION TERM>
         <'(AND)'><PROVISO EXPRESSION>

PROVISO EXPRESSION TERM := <PROVISO HEADER STATEMENT><:><PROVISO FUNCTION
         STATEMENT> 1 <PROVISO EXPRESSION TERM><,><PROVISO FUNCTION
         STATEMENT>
```

STATEMENT CONSTRUCTION

```
NON-METALCUTTING STATEMENT := <SIMPLE NON-METALCUTTING STATEMENT> 1 <STANDARD
         PROCEDURE NON-METALCUTTING STATEMENT>

SIMPLE NON-METALCUTTING STATEMENT := <OPERATION><MACHINE PREPOSITIONAL PHRASE> 1
         <'HEAT TREAT'><MACHINE PREPOSITIONAL PHRASE><'TO SPECIFIED
         HARDNESS'>

STANDARD PROCEDURE NON-METALCUTTING STATEMENT := <SIMPLE NON-METALCUTTING
         STATEMENT><STANDARD PROCEDURE PREPOSITIONAL PHRASE>

SIMPLE METALCUTTING STATEMENT := <OPERATION><SURFACE SPECIFICATION><MACHINE
         PREPOSITIONAL PHRASE> 1 <OPERATION><SURFACE SPECIFICATION>
         <MACHINE PREPOSITIONAL PHRASE><ORIENTATION PREPOSITIONAL PHRASE>

CONTINUED METALCUTTING STATEMENT := <OPERATION><SURFACE SPECIFICATION>

SINGLE FEATURE METALCUTTING STATEMENT := <OPERATION><'THE'><VOCABULARY TERM>
         <MACHINE PREPOSITIONAL PHRASE> 1 <OPERATION><'THE'><VOCABULARY
         TERM><MACHINE PREPOSITIONAL PHRASE><ORIENTATION PREPOSITIONAL
         PHRASE>
```

TABLE D2. COMPUTER PROCESS PLANNING LANGUAGE (COPPL) DEFINITION (Continued)

```
MULTIPLE OPERATION METALCUTTING STATEMENT := <OPERATION><'EACH'><SURFACE
          SPECIFICATION><MACHINE PREPOSITIONAL PHRASE> 1 <OPERATION>
          <'EACH'><SURFACE SPECIFICATION><MACHINE PREPOSITIONAL PHRASE>
          <ORIENTATION PREPOSITIONAL PHRASE>

ORIENTATION STATEMENT := <'ORIENT PART FOR'><VOCABULARY TERM>

TRANSFER STATEMENT := <UNCONDITIONAL TRANSFER STATEMENT> 1 <CONDITIONAL TRANSFER
          STATEMENT>

UNCONDITIONAL TRANSFER STATEMENT := <'DO'><RULE NUMBER>

CONDITIONAL TRANSFER STATEMENT := <UNCONDITIONAL TRANSFER STATEMENT><'IF'>
          <CONDITIONAL TRANSFER PHRASE><,><'ELSE'><RULE NUMBER>

FEATURE CONDITIONAL STATEMENT := <NOUN><VERB><VOCABULARY TERM> 1 <NOUN><VERB>
          <'A'><VOCABULARY TERM> 1 <NOUN><VERB><'AN'><VOCABULARY TERM>

ATTRIBUTE CONDITIONAL STATEMENT := <VOCABULARY TERM><'IS'><RELATION><VALUE> 1
          <VOCABULARY TERM><'IS'><RELATION><ARITHMETIC PHRASE>

PROVISO HEADER STATEMENT := <'PROVIDING'><:> 1 <'PROVIDING'><ALPHANUMERIC
          STRING><:> 1 <'INCLUDING'><:> 1 <'INCLUDING'> <ALPHANUMERIC
          STRING><:>

PROVISO FUNCTION STATEMENT := <VOCABULARY TERM> 1 <VOCABULARY TERM><(>
          <ARGUMENT LIST><)>

END STATEMENT := <'END'>


                    PHRASE CONSTRUCTION
                    -------------------

MACHINE PREPOSITIONAL PHRASE := <PREPOSITION><MACHINE CLASS SPECIFICATION> 1
          <PREPOSITION><MACHINE CLASS SPECIFICATION><'OR'><MACHINE CLASS
          SPECIFICATION> 1 <PREPOSITION><MACHINE CLASS SPECIFICATION><,>
          <MACHINE TOOL SPECIFICATION>

STANDARD PROCEDURE PREPOSITIONAL PHRASE := <'PER'><STANDARD PROCEDURE
          SPECIFICATION> 1 <'PER'><STANDARD PROCEDURE SPECIFICATION><'AND'>
          <STANDARD PROCEDURE SPECIFICATION>

ORIENTATION PREPOSITIONAL PHRASE := <'IN'><PART ORIENTATION SPECIFICATION>
```

TABLE D2. COMPUTER PROCESS PLANNING LANGUAGE (COPPL) DEFINITION (Continued)

```
CONDITIONAL TRANSFER PHRASE := <VOCABULARY TERM><'IS'><RELATION><VALUE> 1
           <VOCABULARY TERM><'IS'><RELATION><VALUE><LABEL> 1 <'PART HAS'>
           <VOCABULARY TERM>

ARITHMETIC PHRASE := <VALUE><ARITHMETIC OPERATOR><VOCABULARY TERM>


                 LOW LEVEL AND PRIMITIVE CONSTRUCTIONS
                 -------------------------------------
RULE NUMBER := <NUMERIC STRING>

CONTINUED RULE NUMBER := <RULE NUMBER><'C'>

OPERATION := <ALPHANUMERIC STRING>

VOCABULARY TERM := <ALPHANUMERIC STRING>

NOUN := <'SURFACE'> 1 <'FEATURE'>

VERB := <'IS'> 1 <'IS NOT'>

RELATION := <'.GT'> 1 <'.LT'> 1 <'.GE'> 1 <'.LE'> 1 <'.EQ'> 1 <'.NE'>

VALUE := <NUMERIC STRING> 1 <.><NUMERIC STRING> 1 <NUMERIC STRING><.> 1
         <NUMERIC STRING><.><NUMERIC STRING>

ARGUMENT LIST := <VALUE> 1 <VALUE><,><ARGUMENT LIST>

PREPOSITION := <'AT'> 1 <'IN'> 1 <'WITH'> 1 <'ON'>

MACHINE CLASS SPECIFICATION := <'MC'><NUMERIC STRING><(><ALPHANUMERIC STRING><)>

MACHINE TOOL SPECIFICATION := <'MT'><NUMERIC STRING><(><ALPHANUMERIC STRING><)>

STANDARD PROCEDURE SPECIFICATION := <ALPHANUMERIC STRING>

PART ORIENTATION SPECIFICATION := <'NORMAL'> 1 <'REVERSE'>

LABEL := <(><ALPHANUMERIC STRING><)>

SURFACE SPECIFICATION := <BASIC SURFACE SPECIFICATION> 1 <LABELED SURFACE
           SPECIFICATION>
```

TABLE D2. COMPUTER PROCESS PLANNING LANGUAGE (COPPL) DEFINITION (Continued)

```
LABELED SURFACE SPECIFICATION := <BASIC SURFACE SPECIFICATION><LABEL>

BASIC SURFACE SPECIFICATION := <'OUTSIDE SURFACE'> 1 <'INSIDE SURFACE'> 1
        <'SURFACE'>

ARITHMETIC OPERATOR := <+> 1 <-> 1 <*> 1 </>
ALPHANUMERIC STRING := <'A'> 1 <'B'> 1 ... 1 <'Z'> 1 <' '> 1 <&> 1 <.> 1
        <NUMERIC STRING> 1 <ALPHANUMERIC STRING><ALPHANUMERIC STRING>

NUMERIC STRING := <'0'> 1 <'1'> 1 ... 1 <'9'> 1 <NUMERIC STRING><NUMERIC STRING>
```

TABLE D2. COMPUTER PROCESS PLANNING LANGUAGE (COPPL) DEFINITION (Concluded)

The last step of language processing is code generation. The code generator produces a numeric computer code that is stored in the CPPP data base and "executed" to produce process plans for parts of a particular part family. The code generation process begins by interpreting the syntax structure produced in the initial language translation step. The conditional expression of an axiom is organized into a "transfer table" from which code can be generated to evaluate the expression when "executed" by CPPP. The transfer table for the axiom shown in the example above is shown in Table D3. The first line can be read . . . "if the surface is an open diameter then transfer to line 5, otherwise transfer to line 2."

TABLE D3. EXAMPLE OF CONDITIONAL EXPRESSION STRUCTURE ORGANIZED AS A TRANSFER TABLE.

Line Number	Condition Or Action	Transfer On True	Transfer On False
1	Open Diameter	5	2
2	Semiopen Diameter	3	4
3	Exposed	5	4
4	End	5	6
5	Cut Surface		
6	Surface Not Cut		

Whenever a transfer is made to line 5, the table says to cut the surface. Conversely, whenever a transfer is made to line 6, the table says the surface is not to be cut.

The code generator produces a sequence of coded instructions that would cause CPPP to operate in a manner equivalent to interpreting the transfer table. An example of the type of instructions generated is shown below:

```
 10    CLL     A      (Open Diameter)
 20    TNZ    90
 30    CLL     B      (Semiopen Diameter)
 40    TZE    70
 50    CLL     C      (Exposed)
 60    TNZ    90
 70    CLL     D      (End)
 80    TZE   100
 90    CLL   CUT
100    CLL  NEXT
```

Line 10 of the coded sequence is an instruction to "call A". This would cause CPPP to transfer control to the vocabulary program OPEN DIAMETER, which would test the particular part surface to determine if it is an open diameter. The program returns a 1 if the answer is true, otherwise a 0 is returned. Line 20 of the coded sequence is an instruction to "transfer on non-zero". Therefore, if OPEN DIAMETER of the previous instruction returns a true indication of 1, the instruction at line 20 will transfer to line 90 which is coded to transfer to a program called CUT -- this program identifies surfaces to be cut in an operation.

The example and discussion provided above are intended only to provide some insight into the code generation procedure. This is a complex program and requires much more space to document than is available in this report.

APPENDIX E

PROCESS DECISION MODEL FOR NITRALLOY SLEEVES

The process decision model used in the CPPP demonstration is given below. CPPP executes this model to generate a sequence of operations for parts in the nitralloy sleeve family.

Nitralloy sleeves are made from bar stock and generally do not exceed six inches in length or two inches in diameter. Parts are characterized by stepped diameters; complex groove patterns; through holes; tight tolerances and surface finish; form conditions of concentricity, straightness and flatness; and rotational and nonrotational features such as radial holes, windows and flats. Also, requirements exist for gas nitriding, copper plating, through hardening, nickel plating, electrofilming and other nonmachining operations.

Figure E1 illustrates the shape variance of parts covered by the process model. The model has been programmed for a large family of parts with significant variances of geometry, machined features, form conditions, etc. The same model with minor modifications could be used for nonnitrided sleeves and other kinds of parts of similar shape that are made from bar stock.

The model is programmed in the Computer Process Planning Language (COPPL) defined in Appendix D. Explanatory notes, identified by an "N" at the right margin, give the motivation for individual process rules or several rules. These notes are not a part of the model executed by CPPP; they are ignored when the model is compiled by the language processor. They are included in the model to provide documentation.

Appendix F explains each of the special vocabulary terms used in the nitralloy sleeve model.

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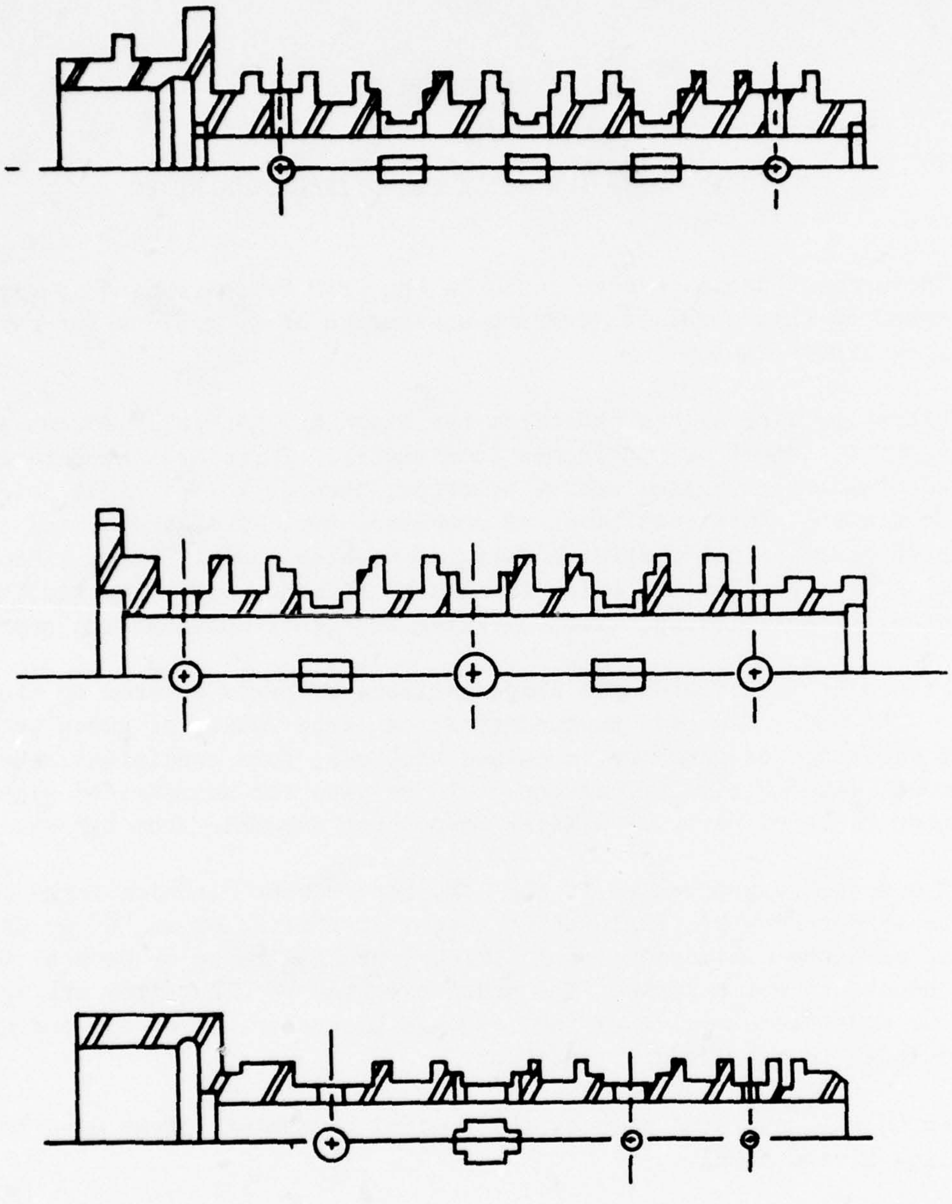

FIGURE E1. ILLUSTRATION OF DESIGN VARIANCE COVERED BY PROCESS DECISION MODEL FOR NITRALLOY SLEEVES

PROCESS DECISION RULES
NITRALLOY SLEEVES

0010 DRAW MATERIAL AT MC0100 (BENCH), MT0108 (BENCH 601001) $

THE NEXT STATEMENT WILL ORIENT (SETUP) THE PART SO THAT THE LONGEST OD OF THE PART IS OPEN TO THE RIGHT SIDE -- THIS WILL BE THE NORMAL ORIENTATION.

0020 ORIENT PART FOR LONGEST OD SETUP $

THE NEXT OPERATION IS PROGRAMMED TO SHAPE THE PART IN NORMAL ORIENTATION. OPEN AND SEMIOPEN (STEPPED) DIAMETERS, THE FREE END AND THE CUT-OFF END WILL BE CUT. DIAMETERS WILL BE CUT ONLY IF THE RESULTING STEP SIZE (SHOULDER) IS AT LEAST .040. ALSO, THE OPERATION MUST RESULT IN AT LEAST ONE DIAMETER BEING AS LONG AS .250 OF THE PART LENGTH.

0030 TURN OUTSIDE SURFACE ON MC0400 (AUTOMATIC BAR MACHINE) IN NORMAL IF

SURFACE IS AN OPEN DIAMETER,
SURFACE IS EXPOSED (OR)

FEATURE IS A SEMIOPEN DIAMETER,
FEATURE IS EXPOSED (OR)

SURFACE IS AN END (AND)

PROVIDING THE FOLLOWING CONDITIONS ARE SATISFIED:

MINIMUM DIAMETER SEPARATION (0.040) ,
RESULTING LONGEST DIAMETER (0.25) $

0040 HEAT TREAT IN MC0200 (FURNACE), MT0201 (FURNACE 2700) TO SPECIFIED
* HARDNESS PER PMP510 $

THE NEXT THREE STATEMENTS ARE PROGRAMMED TO GRIND THE LOCATING OD FOR A DEEP HOLE OPERATION AND TO DRILL THE DEEP HOLE (THRU BORE) USING EITHER AN EJECTOR DRILL OR GUN DRILL.

0050 GRIND THE LONGEST OD ON MC0500 (CENTERLESS GRINDER) $

0060 DRILL THE THRU BORE WITH MC0600 (GUN DRILL) IF

DIAMETER DIMENSION IS .LE 0.787 $

0070 DRILL THE THRU BORE WITH MC2300 (EJECTOR DRILL) IF

DIAMETER DIMENSION IS .GT 0.787 $

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```
       THE NEXT STATEMENT IS PROGRAMMED TO SHAPE THE PART IN REVERSE        N
       ORIENTATION.  ANY OPEN OR SEMIOPEN (STEPPED) OD'S THAT WERE NOT CUT  N
       ON THE BAR MACHINE WILL BE CUT IN THIS OPERATION.  THE LARGEST OD    N
       WILL BE FINISH TURNED (WAS ROUGH CUT ON BAR MACHINE) IF ITS          N
       TOLERANCE IS LESS THAN OR EQUAL TO .010 -- A MORE OPEN TOLERANCE     N
       COULD HAVE BEEN FINISHED ON THE BAR MACHINE.  THE FREE END (CUT-OFF  N
       END) WILL ALSO BE CUT.  RELIEF FEATURES WILL ALSO BE CUT.            N
       COUNTERBORES (STEPPED ID'S) THAT ARE OPEN TO THE FREE END WILL ALSO  N
       BE CUT.  GROOVE FEATURES WILL ALSO BE CUT IF THEY ARE TO BE          N
       INSTALLED IN A COUNTERBORE THAT IS CUT, AND PROVIDING THE GROOVE     N
       IS LOCATED WITHIN .500 OF THE PART LENGTH TO THE FREE END.  IF       N
       COUNTERBORES ARE IDENTIFIED AS ''SHARP EDGE FEATURES'' THEY WILL NOT N
       BE CUT -- THESE FEATURES WILL ULTIMATELY BE INSTALLED BY GRINDING    N
       FOLLOWING ANY NITRIDING OPERATION.                                   N
                                                                            N
0080   TURN OUTSIDE SURFACE ON MC2400 (AUTOMATIC CHUCKER) OR MC2500 (NC LATHE) *
     *  IN REVERSE IF
                                                                            N
           SURFACE IS AN OPEN DIAMETER,
            SURFACE IS NOT CUT,
            SURFACE IS EXPOSED (OR)
                                                                            N
           FEATURE IS A SEMIOPEN DIAMETER,
            FEATURE IS NOT CUT,
            FEATURE IS EXPOSED (OR)
                                                                            N
           SURFACE IS A FREE END (OR)
                                                                            N
           FEATURE IS A GROOVE,
            FEATURE IS NOT A LONGEST OD FEATURE,
            FEATURE IS EXPOSED (OR)
                                                                            N
           FEATURE IS A CHAMFER,
            FEATURE IS NOT A LONGEST OD FEATURE,
            FEATURE IS EXPOSED (OR)
                                                                            N
           FEATURE IS A RELIEF (OR)
                                                                            N
           SURFACE IS A RELIEF FACE (OR)
                                                                            N
           SURFACE IS LARGEST OD,
            SURFACE IS NOT LONGEST OD,
            DIAMETRAL TOLERANCE IS .LE .010  $
                                                                            N
0080C  TURN INSIDE SURFACE IF
                                                                            N
           FEATURE IS A COUNTERBORE,
            FEATURE IS EXPOSED,
            FEATURE IS NOT A SHARP EDGE FEATURE (OR)
                                                                            N
```

```
            FEATURE IS A GROOVE,
             FEATURE IS EXPOSED,
             FEATURE IS A COUNTERBORE FEATURE,
             FEATURE LOCATION IS .LE 0.5*PART LENGTH (OR)

            FEATURE IS A RELIEF (OR)

            SURFACE IS A RELIEF FACE  $

        THE NEXT STATEMENT IS PROGRAMMED TO REMOVE BURRS THAT MIGHT EXIST
        AT THE END OF THE BORE BECAUSE OF THE PREVIOUS OPERATIONS -- THIS
        WILL PROTECT THE SMALL SIZE HONING MANDRELS FROM BREAKING.

0090    HAND REAM THE THRU BORE ON MC0800 (BENCH LAP) IF

            DIAMETER DIMENSION IS .LT 0.375  $

        THE NEXT STATEMENT IS PROGRAMMED TO ACHIEVE A CONSISTENTLY SIZED
        BORE WITH SMOOTH SURFACE SO THAT IT CAN BE USED AS A LOCATING
        SURFACE IN ATTAINING CONCENTRICITY BETWEEN OD'S AND THE THRU BORE.

0100    HONE THE THRU BORE WITH MC0900 (AUTOMATIC HONE) IN NORMAL  $

        THE NEXT STATEMENT IS PROGRAMMED TO ACHIEVE CONCENTRICITY BETWEEN
        THE OD AND THRU BORE   THE OD WILL SERVE AS A LOCATING SURFACE
        FOR THE FINISH TURN.  THE OD FACE WILL BE GROUND IF THERE IS NO
        RELIEF.

0110    GRIND OUTSIDE SURFACE (LONGEST OD) ON MC1000 (OD GRINDER) IN NORMAL IF

            SURFACE IS LONGEST OD (AND)

          INCLUDING THE FOLLOWING:

            CUT DIAMETER FACES  $

        THE NEXT STATEMENT IS PROGRAMMED TO FINISH TURN THE PART IN NORMAL
        ORIENTATION.  SEMIOPEN (STEPPED) OD'S WILL BE CUT PROVIDING THEY
        HAVE ONLY BEEN ROUGH TURNED, AND PROVIDING THEIR TOLERANCE IS
        BETWEEN .004 AND .010, AND ANY CONCENTRICITY REQUIREMENT IS GREATER
        THAN OR EQUAL TO .0020  DIAMETERS WITH TOLERANCE LARGER THAN .010
        COULD HAVE BEEN FINISHED ON BAR MACHINE -- DIAMETERS WITH TOLERANCES
        TIGHTER THAN .004 OR CONCENTRICITIES TIGHTER THAN .002 WILL BE
        GROUND AND NOT FINISH TURNED.  SEMIOPEN DIAMETERS (STEPPED) THAT
        WERE NOT ROUGH TURNED BECAUSE OF SMALL STEP SIZE WILL NOW BE CUT
        IF THEIR TOLERANCE REQUIREMENTS ARE GREATER THAN .004 AND
        CONCENTRICITY REQUIREMENTS ARE GREATER THAN .0020 OTHERWISE
        THEY WILL BE GROUND LATER.  SEMIOPEN DIAMETERS THAT WERE NOT ROUGH
        TURNED AND HAVE TOLERANCE REQUIREMENT LESS THAN .004 WILL BE FINISH
        TURNED IF THE AMOUNT OF THE STOCK TO BE REMOVED IS GREATER THAN
        .015 (SO NOT TO LEAVE A LARGE AMOUNT OF STOCK FOR GRINDING).
```

```
      COUNTERBORES (STEPPED ID'S) THAT ARE OPEN TO THE FREE END WILL ALSO     N
      BE FINISH TURNED, PROVIDING THEY ARE NOT IDENTIFIED AS A SHARP EDGE     N
      FEATURE.  ANY UNCUT GROOVE ''EXPOSED'' TO THE FREE END WILL ALSO BE     N
      CUT.  CHAMFERS ARE ALSO CUT IN THIS OPERATION.  THE FREE END (FACE)     N
      WILL ALSO BE CUT FOR USE AS A REFERENCE SURFACE IN GAGING PROVIDING     N
      OTHER CUTS ARE REQUIRED.                                                N
                                                                              N
0120  TURN OUTSIDE SURFACE ON MC2400 (AUTOMATIC CHUCKER) OR MC2500 (NC LATHE) *
   *    IN NORMAL IF
                                                                              N
          FEATURE IS A SEMIOPEN DIAMETER,
           FEATURE IS EXPOSED,
           FEATURE IS CUT,
           NUMBER OF CUTS IS .LT 2,
           DIAMETRAL TOLERANCE IS .LT .010,
           DIAMETRAL TOLERANCE IS .GE .004,
           CONCENTRICITY IS .GE .002 (OR)
                                                                              N
          FEATURE IS A SEMIOPEN DIAMETER,
           FEATURE IS EXPOSED,
           FEATURE IS NOT CUT,
           DIAMETRAL TOLERANCE IS .GE 0.004,
           CONCENTRICITY IS .GE 0.002 (OR)
                                                                              N
          FEATURE IS A SEMIOPEN DIAMETER,
           FEATURE IS EXPOSED,
           FEATURE IS NOT CUT,
           DIAMETRAL TOLERANCE IS .LT .004,
           SHOULDER HEIGHT IS .GT 0.015 (OR)
                                                                              N
          FEATURE IS A SEMIOPEN DIAMETER,
           FEATURE IS EXPOSED,
           FEATURE IS NOT CUT,
           CONCENTRICITY IS .LT 0.002,
           SHOULDER HEIGHT IS .GT 0.015 (OR)
                                                                              N
          SURFACE IS A FREE END (OR)
                                                                              N
          SURFACE IS A CHAMFER,
           SURFACE IS EXPOSED,
           FEATURE LOCATION IS .LE 0.5*PART LENGTH  $
                                                                              N
0120C TURN INSIDE SURFACE IF
                                                                              N
          FEATURE IS A COUNTERBORE,
           FEATURE IS EXPOSED,
           FEATURE IS NOT CUT,
           FEATURE IS NOT A SHARP EDGE FEATURE (OR)
                                                                              N
```

```
          FEATURE IS A GROOVE,
           FEATURE IS EXPOSED,
           FEATURE IS NOT CUT (OR)

          FEATURE IS CHAMFER,
           FEATURE IS EXPOSED (AND)

        PROVIDING THE FOLLOWING CONDITION EXISTS:

          MULTIPLE CUTS  $

      THE NEXT STATEMENT IS PROGRAMMED TO FINISH GRIND THE CUT-OFF END
      IF ITS LATERAL TOLERANCE IS LESS THAN .001.

0130  GRIND THE FREE END ON MC1100 (SURFACE GRINDER) IN REVERSE IF

          LATERAL TOLERANCE IS .LT 0.001  $

      THE THREE STATEMENTS ARE PROGRAMMED TO INSTALL GROOVES BY CRUSH
      GRINDING   O-SEAL GROOVES ARE INSTALLED FIRST.  SMALL SEMIOPEN
      (STEPPED) DIAMETERS NOT CUT IN TURNING OPERATIONS WILL BE CRUSH
      GROUND WITH THE GROOVES.  CRUSH GROUND GROOVES MUST BE SEPARATED
      BY AT LEAST .060 -- WHEN A PATTERN OF GROOVES HAVE SEPARATIONS
      LESS THAN .060, TWO OPERATIONS ARE NEEDED.

0140  CRUSH GRIND OUTSIDE SURFACE (O.SEAL GROOVES) ON MC1400 (CRUSH GRINDER)
    *  IN NORMAL IF

          FEATURE IS AN O.SEAL GROOVE $

0150  CRUSH GRIND OUTSIDE SURFACE (GROOVES) ON MC1400 (CRUSH GRINDER) IN
    *  NORMAL IF

          FEATURE IS A GROOVE,
           FEATURE IS NOT CUT (OR)

          FEATURE IS A SEMIOPEN DIAMETER,
           FEATURE IS NOT CUT (OR)

          FEATURE IS A SEMIOPEN DIAMETER,
           NUMBER OF CUTS IS .LT 2,
           DIAMETRAL TOLERANCE IS .LT .004 (AND)

        PROVIDING THE FOLLOWING CONDITION EXISTS:

           MINIMUM GROOVE SEPARATION (0.060)  $

0160  CRUSH GRIND OUTSIDE SURFACE (GROOVES) ON MC1400 (CRUSH GRINDER) IN
    *  NORMAL IF

          FEATURE IS A GROOVE,
           FEATURE IS NOT CUT $
```

```
                                                                              N
0170   DEBURR PART IN MC1500 (VIBRATING TUB)  $                              N
0180   STRESS RELIEF IN MC0200 (FURNACE), MT0202 (FURNACE 2790) PER PMP110  $ N

       THE NEXT SEVERAL STATEMENTS ARE PROGRAMMED TO INSTALL SLOTS, FLATS,    N
       WINDOWS, AND HOLES.  IF THE PART HAS A TIMING FEATURE, IT WILL BE      N
       INSTALLED BEFORE FEATURES THAT ARE TIMED.  WINDOWS AND HOLES THAT      N
       BREAK INTO THE BORE WITH A SHARP EDGE REQUIREMENT OR ARE IRREGULARLY   N
       SHAPED WILL NOT BE INSTALLED AT THIS POINT SINCE THEY MUST BE          N
       INSTALLED BY EDM.                                                      N

0190   DO 0200 IF PART HAS TIMING FEATURE REQUIREMENT, ELSE 0230  $          N
0200   ORIENT PART FOR TIMING FEATURE SETUP  $                               N
0210   INSTALL OUTSIDE SURFACE (TIMING FEATURE) ON MC1300 (MILLING MACHINE) IN *
     * NORMAL IF                                                              N

           FEATURE IS A TIMING FEATURE,
            FEATURE IS A SLOT (OR)                                            N

           FEATURE IS A TIMING FEATURE,
            FEATURE IS A FLAT (OR)                                            N

           FEATURE IS A TIMING FEATURE,
            FEATURE IS A WINDOW,
            FEATURE IS A RECTANGULAR WINDOW,
            BORE EDGE BREAK IS .GT 0.005  $

       THE NEXT STATEMENT TESTS TO DETERMINE IF THE TIMING FEATURE WAS CUT    N
       BY THE PREVIOUS OPERATION.  IF CUT, THE PROGRAM WILL INSTALL ANY       N
       OTHER MILLED FEATURES (IE., SLOTS, FLATS, WINDOWS).  IF NOT CUT,       N
       THE PROGRAM WILL NEXT INSTALL HOLES BEFORE INSTALLING MILLED           N
       FEATURES   IF THE TIMING FEATURE IS A HOLE IT WILL BE INSTALLED        N
       FIRST.                                                                 N

0220   DO 260 IF PART HAS CUT TIMING FEATURE, ELSE 0230  $                   N
0230   DRILL OUTSIDE SURFACE (HOLES) ON MC1200 (DRILL PRESS) IN NORMAL IF    N

           FEATURE IS A LONGITUDINAL HOLE,
            FEATURE IS EXPOSED (OR)                                           N

           FEATURE IS A RADIAL HOLE,
            FEATURE IS EXPOSED,
            BORE EDGE BREAK IS .GT 0.005 (AND)                                N

         PROVIDING THE FOLLOWING CONDITION EXISTS:                            N

           TIMING CONDITION MET  $                                            N
```

```
0240   DRILL OUTSIDE SURFACE (HOLES) ON MC1200 (DRILL PRESS) IN REVERSE IF      N

             FEATURE IS A LONGITUDINAL HOLE,                                     N
              FEATURE IS NOT CUT,
              FEATURE IS EXPOSED (OR)
                                                                                 N
             FEATURE IS A RADIAL HOLE,
              FEATURE IS NOT CUT,
              FEATURE IS EXPOSED,
              BORE EDGE BREAK IS .GT 0.005 (AND)
                                                                                 N
          PROVIDING THE FOLLOWING CONDITION EXISTS:                              N

             TIMING CONDITION MET  $                                             N

0250   DO 0260 IF PART HAS CUT TIMING FEATURE, ELSE 0270  $                      N

0260   DEBURR TIMING FEATURE AT MC0100 (BENCH), MT0102 (BENCH 060002)  $         N

0270   MILL EACH OUTSIDE SURFACE (FLAT) ON MC1300 (MILLER) IN NORMAL IF          N

             FEATURE IS A FLAT,
              FEATURE IS NOT CUT,
              FEATURE IS EXPOSED (AND)
                                                                                 N
          PROVIDING THE FOLLOWING CONDITION EXISTS:                              N

             TIMING CONDITION MET  $                                             N

0280   MILL EACH OUTSIDE SURFACE (FLAT) ON MC1300 (MILLER) IN REVERSE IF         N

             FEATURE IS A FLAT,
              FEATURE IS NOT CUT,
              FEATURE IS EXPOSED (AND)
                                                                                 N
          PROVIDING THE FOLLOWING CONDITION EXISTS:                              N

             TIMING CONDITION MET  $                                             N

0290   MILL EACH OUTSIDE SURFACE (SLOT) ON MC1300 (MILLER) IN NORMAL IF          N

             FEATURE IS A SLOT,
              FEATURE IS NOT CUT,
              FEATURE IS EXPOSED (AND)
                                                                                 N
          PROVIDING THE FOLLOWING CONDITION EXISTS:                              N

             TIMING CONDITION MET  $                                             N
```

```
0300   MILL EACH OUTSIDE SURFACE (SLOT) ON MC1300 (MILLER) IN REVERSE IF        N

          FEATURE IS A SLOT,
           FEATURE IS NOT CUT,
           FEATURE IS EXPOSED (AND)                                              N

        PROVIDING THE FOLLOWING CONDITION EXISTS:                                N

          TIMING CONDITION MET  $                                                N

0310   MILL EACH OUTSIDE SURFACE (WINDOW) ON MC1300 (MILLER) IN NORMAL IF       N

          FEATURE IS A WINDOW,
           FEATURE IS NOT CUT,
           FEATURE IS EXPOSED,
           BORE EDGE BREAK IS .GT 0.005,
           FEATURE IS A RECTANGULAR WINDOW (AND)                                 N

        PROVIDING THE FOLLOWING CONDITION EXISTS:                                N

          TIMING CONDITION MET  $                                                N

0320   MILL EACH OUTSIDE SURFACE (WINDOW) ON MC1300 (MILLER) IN REVERSE IF      N

          FEATURE IS A WINDOW,
           FEATURE IS NOT CUT,
           FEATURE IS EXPOSED,
           BORE EDGE BREAK IS .GT 0.005,
           FEATURE IS A RECTANGULAR WINDOW (AND)                                 N

        PROVIDING THE FOLLOWING CONDITION EXISTS:                                N

          TIMING CONDITION MET  $                                                N

       THE NEXT TWO STATEMENTS ARE PROGRAMMED TO INSTALL HOLES -- IF THE        N
       TIMING FEATURE IS INSTALLED BY MILLING, HOLES ARE INSTALLED AFTER        N
       ALL MILLED FEATURES ARE INSTALLED.  IF HOLES HAVE ALREADY BEEN           N
       INSTALLED BY A PREVIOUS STATEMENT, THE FOLLOWING TWO STATEMENTS          N
       WILL NOT RESULT IN AN OPERATION.                                          N
                                                                                 N
                                                                                 N
0330   DRILL OUTSIDE SURFACE (HOLES) ON MC1200 (DRILL PRESS) IN NORMAL IF       N

          FEATURE IS A LONGITUDINAL HOLE,
           FEATURE IS NOT CUT,
           FEATURE IS EXPOSED (OR)                                               N

          FEATURE IS A RADIAL HOLE,
           FEATURE IS NOT CUT,
           FEATURE IS EXPOSED,
           BORE EDGE BREAK IS .GT 0.005 (AND)                                    N
```

```
         PROVIDING THE FOLLOWING CONDITION EXISTS:                          N
            TIMING CONDITION MET  $                                         N
0340   DRILL OUTSIDE SURFACE (HOLES) ON MC1200 (DRILL PRESS) IN REVERSE IF  N

            FEATURE IS A LONGITUDINAL HOLE,
             FEATURE IS NOT CUT,
             FEATURE IS EXPOSED (OR)                                        N

            FEATURE IS A RADIAL HOLE,
             FEATURE IS NOT CUT,
             FEATURE IS EXPOSED,
             BORE EDGE BREAK IS .GT 0.005 (AND)                             N
         PROVIDING THE FOLLOWING CONDITION EXISTS:                          N
            TIMING CONDITION MET  $                                         N
0350   DO 0360 IF PART HAS CUT SLEEVE FEATURE, ELSE 0370  $                 N
0360   DEBURR PART AT MC0100 (BENCH), MT0102 (BENCH 060002)  $              N
       THE NEXT SET OF STATEMENTS ARE PROGRAMMED TO NITRIDE THE PART  THES  N
       THRU BORE OR COUNTERBORE SURFACES MAY BE NITRIDED.  PRIOR TO THE     N
       NITRIDING, THE NON-NITRIDED SURFACES OF THE PART ARE COPPER PLATED   N
       FOR PROTECTION, AND THE THRU BORE IS HONED TO PRE-NITRIDE SIZE,      N
       AND COUNTERBORE SURFACES TO BE NITRIDED ARE GROUND.                  N
0370   MASK NITRIDED SURFACES AT MC0100 (BENCH), MT0103 (BENCH 4876) IF     N
            SURFACE IS A NITRIDED SURFACE  $                                N
0380   COPPER PLATE PART AT MC0300 (TANK), MT0301 (TANK 4825) PER PMP210  $ N
0390   UNMASK PART IN MC0300 (TANK), MT0301 (TANK 4825) $                   N
0400   HONE THE THRU BORE ON MC0900 (AUTOMATIC HONE) IN NORMAL  $           N
0410   GRIND INSIDE SURFACE (NITRIDED SURFACES) ON MC1600 (ID GRINDER) IN   N
     *  REVERSE IF                                                          *
                                                                            N
            SURFACE IS A NITRIDED SURFACE,
             SURFACE IS NOT A THRU BORE,
             SURFACE IS EXPOSED  $                                          N
0420   GRIND INSIDE SURFACE (NITRIDED SURFACES) ON MC1600 (ID GRINDER) IN   *
     *  NORMAL IF                                                           N

            SURFACE IS A NITRIDED SURFACE,
             SURFACE IS NOT A THRU BORE,
             SURFACE IS EXPOSED  $                                          N
```

```
0430    NITRIDE IN MC0200 (FURNACE), MT0203 (FURNACE 2780) PER HS1173 AND      *
     *   PMP505 IF
                                                                                N
             SURFACE IS A NITRIDED SURFACE $                                    N
0440    STRIP COPPER PLATE IN MC0300 (TANK), MT0302 (TANK 4826) PER PMP210  $   N
0450    FPI AT MC0100 (BENCH), MT0104 (BENCH 7560) PER PMP525 AND HS447  $      N

        THE NEXT STATEMENTS ARE PROGRAMMED TO NICKEL PLATE THE PART             N
        WHENEVER SPECIFIED IN THE PART DESIGN.                                  N
                                                                                N
                                                                                N
0460    DO 0470 IF PART HAS NICKEL PLATE REQUIREMENT, ELSE 0490  $              N
0470    MASK FOR NICKEL PLATE AT MC0100 (BENCH), MT0103 (BENCH 4876) IF         N

             SURFACE IS NOT NICKEL PLATED,
              SURFACE IS CUT  $
                                                                                N
0480    NICKELPLATE IN MC0300 (TANK), MT0305 (TANK 4870) PER PMP220 AND HS201  *
     *   IF
                                                                                N
             SURFACE IS NICKEL PLATED $

        THE NEXT SEVERAL STATEMENTS ARE PROGRAMMED TO INSTALL ANY WINDOW        N
        OR HOLE FEATURE THAT COULD NOT BE INSTALLED BY MILLING PRIOR TO         N
        THE NITRIDING PROCESS.  IF THERE IS A TIMING FEATURE THAT HAS NOT       N
        YET BEEN CUT, IT WILL BE INSTALLED FIRST.                               N
                                                                                N
                                                                                N
0490    DO 0520 IF PART HAS CUT TIMING FEATURE, ELSE 0500  $                    N
0500    ORIENT PART FOR TIMING FEATURE SETUP  $                                 N
0510    EDM OUTSIDE SURFACE (TIMING FEATURE) ON MC1800 (EDM MACHINE) IF         N

             FEATURE IS A TIMING FEATURE  $                                     N
0520    EDM OUTSIDE SURFACE (HOLES) ON MC1800 (EDM MACHINE) IF                  N

             FEATURE IS A LONGITUDINAL HOLE,
              FEATURE IS NOT CUT (OR)                                           N

             FEATURE IS A RADIAL HOLE,
              FEATURE IS NOT CUT  $
                                                                                N
0530    EDM OUTSIDE SURFACE (WINDOWS) ON MC1800 (EDM MACHINE) IF                N

             FEATURE IS A WINDOW,
              FEATURE IS NOT CUT  $                                             N
```

```
       THE NEXT SET OF STATEMENTS ARE PROGRAMMED TO REMOVE THE ''WHITE
       LAYER'' FROM NITRIDED SURFACES (IE., THRU BORE AND COUNTERBORES).
       FACES ADJACENT TO GROUND DIAMETERS WILL ALSO BE GROUND.  EACH
       DIAMETER WILL BE GROUND IN A SEPARATE OPERATION.

0540   HONE THE THRU BORE WITH MC1780 (HAND HONE)  $

0550   DEBURR THRU BORE AT MC0100 (BENCH), MT0110 (BENCH 060004)  $

0560   GRIND EACH INSIDE SURFACE ON MC1600 (ID GRINDER) IN REVERSE IF

            SURFACE IS A NITRIDED SURFACE,
             SURFACE IS NOT A THRU BORE,
             SURFACE IS EXPOSED (AND)

         INCLUDING THE FOLLOWING:

            CUT DIAMETER FACES  $

0570   GRIND EACH INSIDE SURFACE ON MC1600 (ID GRINDER) IN NORMAL IF

            SURFACE IS A NITRIDED SURFACE,
             SURFACE IS NOT A THRU BORE,
             SURFACE IS EXPOSED (AND)

         INCLUDING THE FOLLOWING:

            CUT DIAMETER FACES  $

       THE NEXT TWO STATEMENTS ARE PROGRAMMED TO FINISH GRIND ID'S THAT
       HAVE TOLERANCES LESS THAN .0008.  EACH DIAMETER WILL BE GROUND IN
       A SEPARATE OPERATIONS.

0580   GRIND EACH INSIDE SURFACE ON MC1600 (ID GRINDER) IN REVERSE IF

            SURFACE IS A DIAMETER,
             SURFACE IS NOT THRU BORE,
             SURFACE IS EXPOSED,
             SURFACE IS NOT A NITRIDED SURFACE,
             DIAMETRAL TOLERANCE IS .LT .0020  $

0590   GRIND EACH INSIDE SURFACE ON MC1600 (ID GRINDER) IN NORMAL IF

            SURFACE IS A DIAMETER,
             SURFACE IS NOT THRU BORE,
             SURFACE IS EXPOSED,
             SURFACE IS NOT A NITRIDED SURFACE,
             DIAMETRAL TOLERANCE IS .LT .0020  $

       THE NEXT TWO STATEMENTS ARE PROGRAMMED TO FINISH GRIND SHARP EDGE
       FEATURES LOCATED AT THE END OF THE BORE.
```

```
0600   GRIND INSIDE SURFACE (DIAMETERS) ON MC1600 (ID GRINDER) IN REVERSE IF       N
            FEATURE IS A SHARP EDGE FEATURE,
             FEATURE IS EXPOSED  $                                                 N
0610   GRIND INSIDE SURFACE (DIAMETERS) ON MC1600 (ID GRINDER) IN NORMAL IF        N
            FEATURE IS A SHARP EDGE FEATURE,
             FEATURE IS EXPOSED  $                                                 N
       THE NEXT SET OF STATEMENTS ARE PROGRAMMED TO LAP ID SURFACES                N
       REQUIRING EXTREMELY TIGHT TOLERANCES OR SURFACE FINISH.                     N
                                                                                   N
0620   LAP THE THRU BORE ON MC1700 (HAND HONE) IN NORMAL IF                        N
            SURFACE FINISH IS .LE 8 (OR)                                           N
            DIAMETRAL TOLERANCE IS .LE .0004 (OR)                                  N
            STRAIGHTNESS IS .LE .0001 (OR)                                         N
            ROUNDNESS IS .LE .0001  $                                              N
0630   LAP EACH INSIDE SURFACE (DIAMETER) WITH MC0800 (BENCH LAP) IN NORMAL IF     N
            SURFACE IS A DIAMETER,
             SURFACE IS NOT A THRU BORE,
             SURFACE IS EXPOSED,
             SURFACE FINISH IS .LE 8 (OR)                                          N
            SURFACE IS A DIAMETER,
             SURFACE IS NOT A THRU BORE,
             SURFACE IS EXPOSED,
             DIAMETRAL TOLERANCE IS .LE .0004 (OR)                                 N
            SURFACE IS A DIAMETER,
             SURFACE IS NOT A THRU BORE,
             SURFACE IS EXPOSED,
             STRAIGHTNESS IS .LE .0002 (OR)                                        N
            SURFACE IS A DIAMETER,
             SURFACE IS NOT A THRU BORE,
             SURFACE IS EXPOSED,
             ROUNDNESS IS .LE .0001  $                                             N
0640   LAP EACH INSIDE SURFACE (DIAMETER) WITH MC0800 (BENCH LAP) IN5REVERSE5      *
     *  IF                                                                         N
            SURFACE IS A DIAMETER,
             SURFACE IS NOT A THRU BORE,
             SURFACE IS EXPOSED,
             SURFACE FINISH IS .LE 8 (OR)
```

```
              SURFACE IS A DIAMETER,                                          N
               SURFACE IS NOT A THRU BORE,
               SURFACE IS EXPOSED,
               DIAMETRAL TOLERANCE IS .LE .0004 (OR)

              SURFACE IS A DIAMETER,                                          N
               SURFACE IS NOT A THRU BORE,
               SURFACE IS EXPOSED,
               STRAIGHTNESS IS .LE .0002 (OR)

              SURFACE IS A DIAMETER,                                          N
               SURFACE IS NOT A THRU BORE,
               SURFACE IS EXPOSED,
               ROUNDNESS IS .LE .0001  $
                                                                              N
         THE NEXT SET OF STATEMENTS ARE PROGRAMMED TO GENERATE OPERATIONS FOR N
         INSPECTING, MARKING, CLEANING AND PACKING THE PART.                  N
                                                                              N
0650     SAMPLE STRAIGHTNESS OF THRU BORE WITH MC1900 (PROFICORDER) $

0660     SAMPLE ROUNDNESS OF THRU BORE WITH MC2000 (TALYROND), MT2001         N
      *   (TALYROND)  $                                                       *

0670     DEBURR AT MC0100 (BENCH), MT0110 (BENCH 060004)  $                   N

0680     SONIC CLEAN IN MC0300 (TANK), MT0303 (TANK 6225)  $                  N

0690     MARK PART AT MC0100 (BENCH), MT0111 (BENCH 390005)  $                N

0700     WASH PART IN MC0300 (TANK), MT0304 (TANK 6286)  $                    N

0710     ELECTROFILM AT MC0100 (BENCH), MT0106 (BENCH 4875) IF                N

              SURFACE IS AN ELECTROFILM SURFACE  $                            N

0720     FINAL INSPECTION AT MC0100 (BENCH), MT0107 (BENCH 7020)  $           N

0730     CLEAN PRESERVE PACK & DELIVER AT MC0100 (BENCH), MT0109 (BENCH       N
      *   600007)  $                                                          *

0740     END  $                                                               N
```

APPENDIX F

VOCABULARY PROGRAMS

Process decision modeling enables process planners to develop their own vocabulary when expressing the models in the special computer process planning language (COPPL). CPPP requires that each vocabulary term be defined and implemented in the form of a "vocabulary program." These programs are executed by CPPP for each occurrence of the respective vocabulary terms in the process decision models. Each vocabulary program is programmed to perform one of six general functions:

1. Perform logical test for part surface/feature. These programs answer "true" or "false" for a given part surface or feature. For example, the program for "semiopen diameter" determines whether a given surface is part of a semiopen diameter.

2. Determine quantitative attribute of part surface/feature. These programs retrieve or calculate a numerical value associated with a particular attribute of a given surface or feature. "Diametral tolerance," for instance, retrieves the diametral tolerance of a surface.

3. Perform logical test for the part. Here a "true" or "false" condition is determined for the part as a whole. One such program is "nickel plate requirement," which gives a positive answer if any portion of the part is to be nickel plated.

4. Determine quantitative attribute of part. These programs retrieve or calculate a quantitative attribute of the part as a whole. "Part length," for example, returns the finished length of the part being planned.

5. Test acceptance of defined operation. These programs may modify the list of part surfaces/features participating in an operation. They add or delete surfaces/features from an operation or leave the operation as initially defined by the process decision rule. For example, the vocabulary program "minimum diameter separation" will selectively eliminate diameters from being cut in an operation if adjacent diameters are not separated by a specified minimum distance.

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6. Establish standard part orientation. This type of program sets the normal part orientation. Subsequent uses of the words "normal" or "reverse" in process rules are interpreted accordingly. For instance, "longest OD setup" establishes the normal setup orientation as that in which the longest outside diameter of the part is exposed for machining.

As the functional classification above suggests, the use of vocabulary terms in a process decision model must be compatible with their context. Table F1 identifies the appropriate use of each vocabulary class in terms of the language constructions specified in Appendix D.

TABLE F1. VOCABULARY TERM USAGE

Class	Function	COPPL Usage
1	Perform surface logical test	Feature conditional statement Single feature metalcutting statement
2	Access surface attribute	Attribute conditional statement
3	Perform part logical test	Conditional transfer statement
4	Access part attribute	Attribute conditional statement Conditional transfer statement
5	Test acceptance of operation	Proviso function statement
6	Orient part	Orientation statement

Table F2 lists the vocabulary terms used in formulating the process decision model for nitralloy sleeves. The model is given in Appendix E. A brief description of each vocabulary program is provided below.

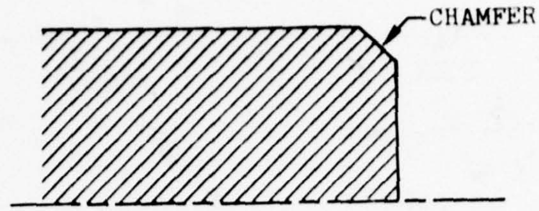
TABLE F2. VOCABULARY TERMS

Term	Class	Term	Class
Bore Edge Break	2	Multiple Cuts	5
Chamfer	1	Nickel Plate Requirement	3
Concentricity	2	Nickel Plated	1
Counterbore	1	Nitrided Surface	1
Counterbore Feature	1	Number of Cuts	2
Cut	1	Open Diameter	1
Cut Diameter Faces	5	O.Seal Groove	1
Cut Sleeve Feature	3	Part Length	4
Cut Timing Feature	3	Radial Hole	1
Diameter	1	Rectangular Window	1
Diameter Dimension	2	Relief	1
Diametral Tolerance	2	Relief Face	1
Electrofilm Surface	1	Resulting Longest Diameter	5
End	1	Roundness	2
Exposed	1	Semiopen Diameter	1
Feature Location	2	Sharp Edge Feature	1
Flat	1	Shoulder Height	2
Free End	1	Slot	1
Groove	1	Straightness	2
Largest OD	1	Surface Finish	2
Lateral Tolerance	2	Thru Bore	1
Longitudinal Hole	1	Timing Condition Met	5
Longest OD	1	Timing Feature	1
Longest OD Feature	1	Timing Feature Requirement	3
Longest OD Setup	6	Timing Feature Setup	6
Minimum Diameter Separation	5	Window	1
Minimum Groove Separation	5		

CLASS 1 -- PERFORM SURFACE LOGICAL TEST

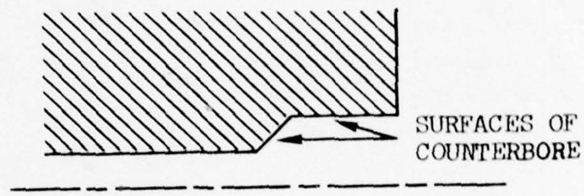
CHAMFER

Determines if a feature is a chamfer or countersink.



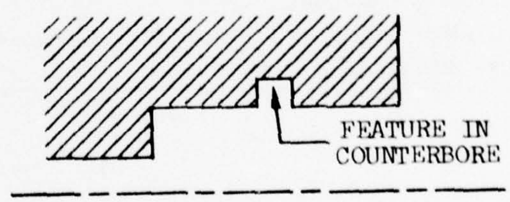
COUNTERBORE

Determines if a part surface is a surface of a counterbore feature. The surface can be either an internal diameter that is open to one end of the bore or the upstepping vertical or tapered surface intersecting with the counterbore internal diameter.



COUNTERBORE FEATURE

Determines if a feature is installed in a counterbore surface.

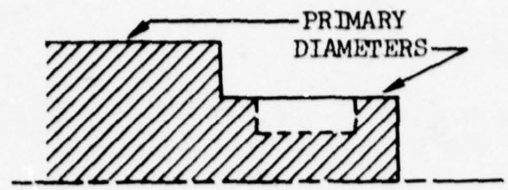


CUT

Determines if a surface or feature has been cut in a previous operation.

DIAMETER

Determines whether a surface is a primary diameter; the diameters of a feature are not considered primary diameters.

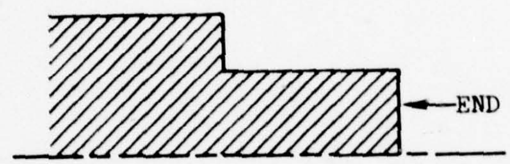


ELECTROFILM SURFACE

Determines if a surface or feature has an electrofilm requirement.

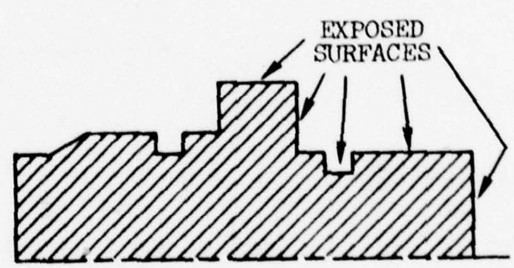
END

Determines if a surface is an end of the part.



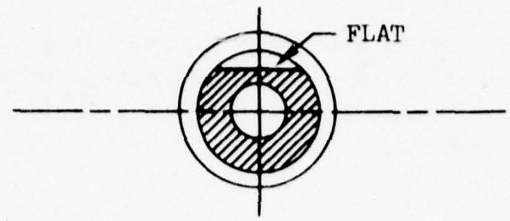
EXPOSED

Determines if a part surface or feature is "open" as seen by line of sight from the free end of the part. A surface is not exposed if there is an interference in the line of sight. Machined features (e.g., grooves) are exposed if their parent surfaces are exposed.



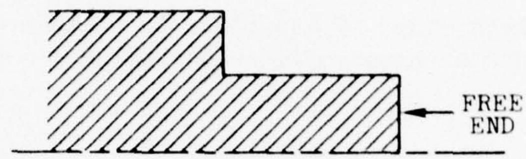
FLAT

Determines if the feature is a flat or whether there is a pattern of flats (e.g., multiple flats angularly displaced around the circumference).



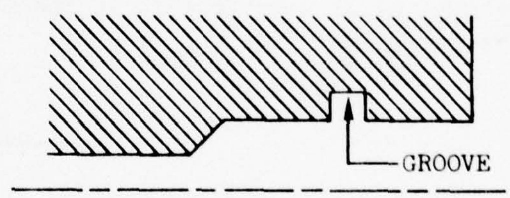
FREE END

Determines if a surface is the exposed end of the part (the right end in a setup).



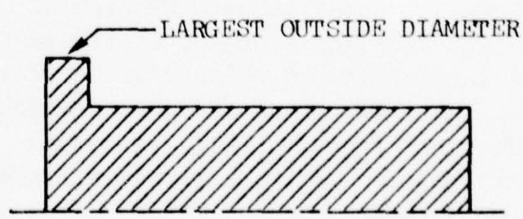
GROOVE

Determines if a feature is a groove.



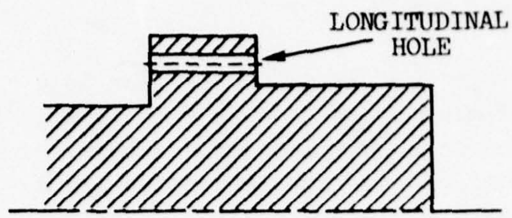
LARGEST OD

Determines if a part surface is the largest outside diameter.



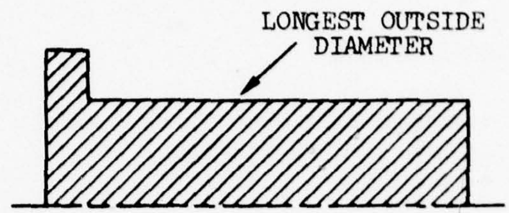
LONGITUDINAL HOLE

Determines whether a feature is a longitudinal hole (the axis of the hole is parallel to the part center line) or whether there is a hole pattern (e.g., bolt hole circle).



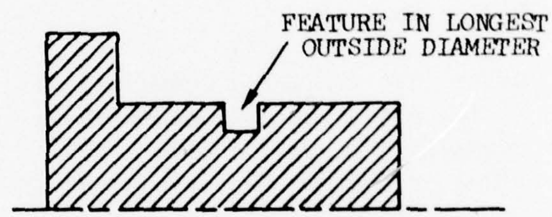
LONGEST OD

Determines whether a surface is the longest uninterrupted outside diameter.



LONGEST OD FEATURE

Determines if the feature is installed in the longest outside diameter.



NICKEL PLATED

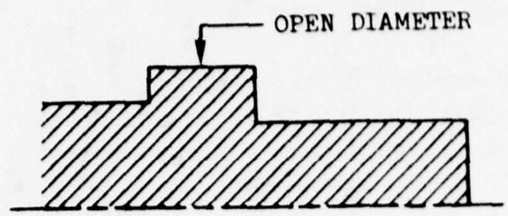
Determines if a surface or feature is to be nickel plated.

NITRIDED SURFACE

Determines if a surface or feature is to be nitrided.

OPEN DIAMETER

Determines if a part surface is a diameter open on both ends (i.e., does not intersect with other surfaces to form upstepping shoulders).

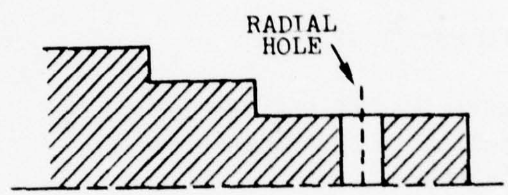


O.SEAL GROOVE

Determines if a feature is identified as an O.seal groove.

RADIAL HOLE

Determines whether a feature is a radial hole (the axis of the hole is perpendicular to the part center line) or whether there is a radial hole pattern (e.g., multiple holes angularly displaced around the circumference).

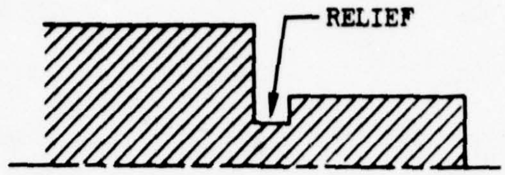


RECTANGULAR WINDOW

Determines if a feature is a window of rectangular shape.

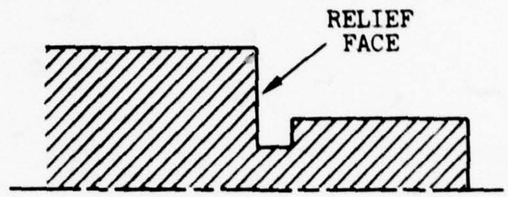
RELIEF

Determines if a feature is a relief.



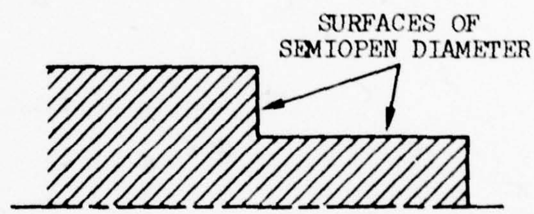
RELIEF FACE

Determines if a part surface is a face extending out from a relief feature.



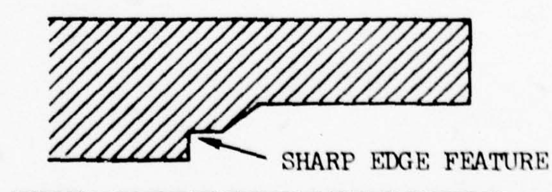
SEMIOPEN DIAMETER

Determines if a surface is either the shoulder (vertical or tapered) or diameter of a semiopen diameter.



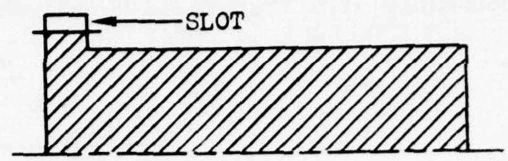
SHARP EDGE FEATURE

Determines if a part surface is the diameter or face (vertical or tapered) of a counterbore with a width and height less than or equal to .020. This counterbore must be adjacent to the thru bore.



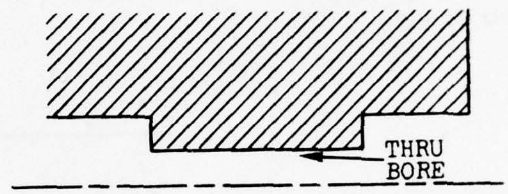
SLOT

Determines if a feature is a slot or whether there is a pattern of slots (e.g., multiple slots angularly displaced around the circumference).



THRU BORE

Determines if an internal diameter is the smallest one and is open to both ends of the part.

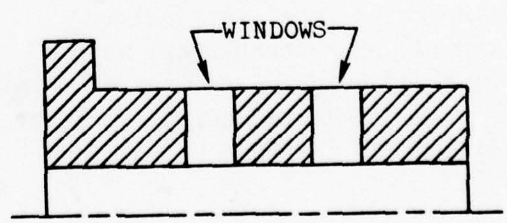


TIMING FEATURE

Determines if a feature is a timing feature.

WINDOW

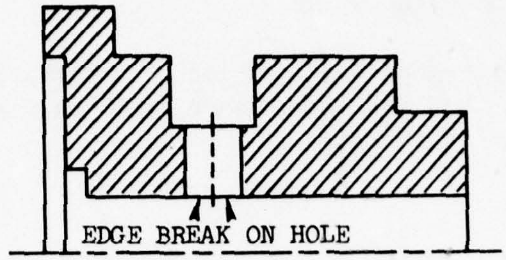
Determines whether a feature is a window or window pattern (e.g., multiple windows angularly displaced around the circumference).



CLASS 2 -- ACCESS SURFACE ATTRIBUTE

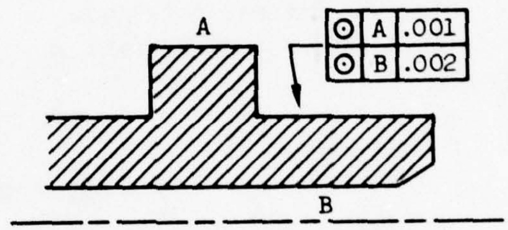
BORE EDGE BREAK

Accesses the edge break condition at the intersection of the feature (hole or window) and the bore.



CONCENTRICITY

Determines the tightest concentricity condition associated with a diameter. If there is no concentricity requirement, a large default value is returned.



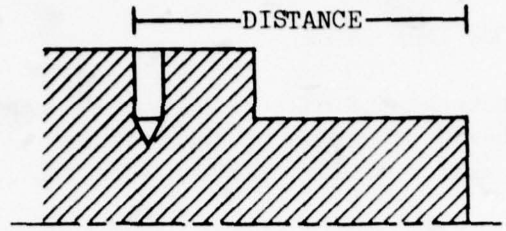
DIAMETER DIMENSION

Retrieves the dimensional value of a diameter surface.

DIAMETRAL TOLERANCE

Retrieves the dimensional tolerance of a diameter surface.

FEATURE LOCATION



Determines the location of a feature as the lateral distance from the free end of the part.

LATERAL TOLERANCE

Retrieves the lateral tolerance associated with a part surface or feature.

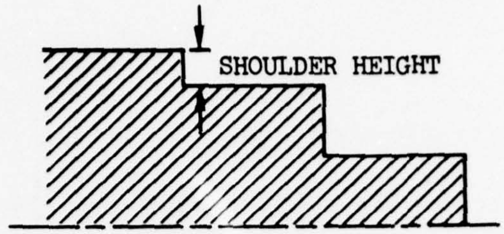
NUMBER OF CUTS

Determines the number of cuts that have been made on a surface or feature.

ROUNDNESS

Retrieves the roundness condition associated with a diameter. If there is no roundness requirement, a default value is returned.

SHOULDER HEIGHT



Determines the height of the shoulder associated with stepped outside diameters or inside diameters.

STRAIGHTNESS

Retrieves the straightness condition associated with a diameter. If there is no straightness requirement, a default value is returned.

SURFACE FINISH

Accesses the finish specified for a surface. If there is no surface finish requirement, the program returns a default value.

CLASS 3 -- PERFORM PART LOGICAL TEST

CUT SLEEVE FEATURE

Determines if a sleeve feature (slot, flat, window or hole) has been cut in a previous operation.

CUT TIMING FEATURE

Determines if a feature designated as the timing feature has been cut in a previous operation. If the part does not have a timing feature, the vocabulary program will return a default answer.

NICKEL PLATE REQUIREMENT

Determines whether the part has at least one surface or feature that is to be nickel plated.

TIMING FEATURE REQUIREMENT

Determines if the part has a timing feature control for installing other features.

CLASS 4 -- ACCESS PART ATTRIBUTE

PART LENGTH

Determines the overall length of the part.

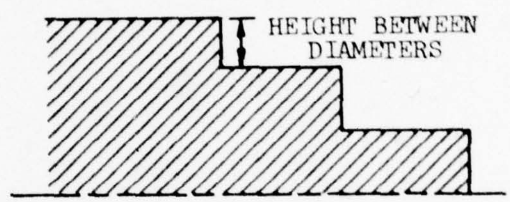
CLASS 5 -- TEST ACCEPTANCE OF OPERATION

CUT DIAMETER FACES

Adds a face or taper of a semi-open diameter or counterbore to the list of surfaces to be cut if its adjacent diameter is to be cut in the operation and there is no cut relief feature.

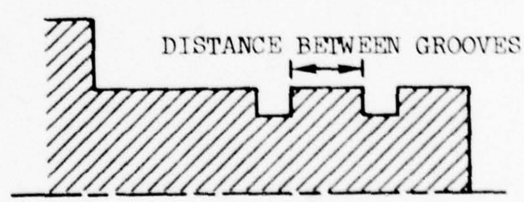
MINIMUM DIAMETER SEPARATION (X)

Determines if the distance between adjacent diameters formed by the operation is at least equal to a specified minimum (x). The program determines the combination of cuts to be made if these diameter separations are less than the minimum value.



MINIMUM GROOVE SEPARATION (X)

Determines if the distance between adjacent grooves formed in the operation is at least equal to a specified minimum (x). This program determines which grooves should be deleted from the operation if there are separations less than the minimum.



MULTIPLE CUTS

Determines if more than one surface is cut in this operation. If not, the program will delete the operation.

RESULTING LONGEST DIAMETER (X)

Determines if the length of the longest diameter formed in the operation is equal to or longer than a specified percentage (x) of the part length. If the length is less than the minimum, the program will delete the cut(s) so that the remaining diameters to be formed are equal to or longer than the minimum.

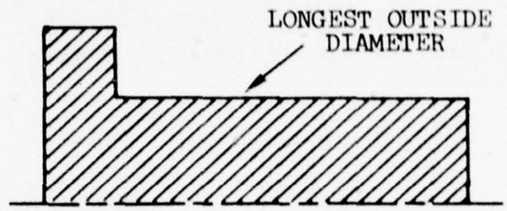
TIMING CONDITION MET

Determines if the timing feature of each feature (e.g., flat, slot, window, hole) to be cut has also been cut or will be cut in the same operation. If a feature has no timing feature requirement, the condition is considered met. The program will eliminate any feature from the operation whose timing feature is not cut.

CLASS 6 -- ORIENT PART

LONGEST OD SETUP

Orients the part so that the longest outside diameter is located on the exposed side of the part in normal orientation.



TIMING FEATURE SETUP

Orients the part so that the timing feature will be open (exposed) to the right side. If the timing feature can be seen from either side, the part will be oriented so that the feature is closest to the right side.

APPENDIX G

TYPES OF CUTS

Detailing of a metalcutting operation includes determination of the type of cut made on each part surface or feature machined in the operation. CPPP uses cut application programs to make this determination. (See 2.3.3.)

For each machine tool in the CPPP data base, there is a list of the types of cuts the machine can make. Associated with each cut type is a computer program that tests the workpiece data for the particular cut. When CPPP plans an operation for a machine tool and cut sequence, the appropriate type of cut is determined for each cut in turn. This is done by invoking the machine's cut application programs until the applicable one is encountered. Thus, a cut application program is programmed as a logical function. It responds "true" or "false" to the proposition that its associated type of cut is appropriate for a given part surface or feature to be cut in the operation .

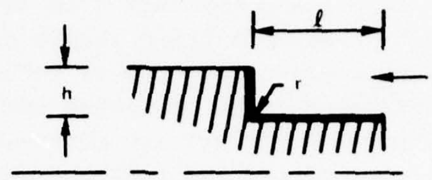
Table G1 lists the types of cuts available in the demonstration CPPP system. The remainder of this appendix gives a description of each cut application program.

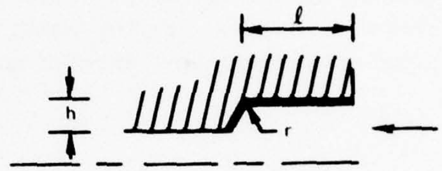
TABLE G1. TYPES OF CUTS

Turn and Form Shoulder or Radius	Form Chamfer
Bore and Form Shoulder or Radius	Drill Bore
Face and Form Diameter or Radius	Drill Bore and Bore
Turn and Face	Drill Bore and Ream
Bore and Face	Drill Hole
Face and Turn	Drill Hole and Ream
Face and Bore	Countersink
Turn and Clear Shoulder	Grind Diameter
Bore and Clear Shoulder or End of Bore	Grind Face
Face and Clear Diameter	Grind End
Turn Open Diameter	Grind Diameter and Face
Bore Open Diameter	Crush Grind
Face Open	Hone Diameter
Cutoff	Lap Diameter
Generate Contour	Mill Feature
Form Tapered Contour	EDM Feature
Form Groove	Shape Feature
Plunge and Cut Groove	Tap Holes
Form Fin	

TURN AND FORM SHOULDER OR RADIUS
BORE AND FORM SHOULDER OR RADIUS

An upstepping external shoulder or downstepping internal shoulder is formed by the shape of the cutting tool. The shoulder may be a straight surface or a radius. The included angle may vary from 90° to 135°, with a maximum taper length of .400, depending on the type of lathe control and whether a rough or finish cut is made. Tapered shoulders are generated on NC or tracer controlled lathes except for rough cuts where standard cutter tools can be used. One or more cuts may be required, depending on the amount of stock removed in each cutting pass. The parameters of the cuts are specified below:

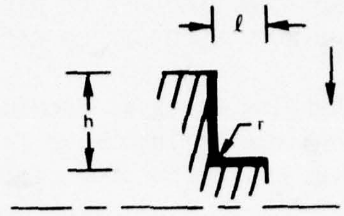


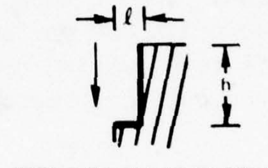


Type of Machine	Manual, Automatic Semiautomatic		Numerical Control, Tracer Lathe	
Type of Cut	rough	finish	rough	finish
Included Angle	90-135	90-135	90, 105, 120, 135	90
Shoulder Height (A = 90°)	≤.400	≤.100	≤.400	≤.100
Taper Length (A > 90°)	≤.400	≤.100	≤.400	N/A
Radius	≤.250	≤.125	≤.125	≤.125
ℓ/h	≥1.0	≥1.0	≥1.0	≥1.0

FACE AND FORM DIAMETER OR RADIUS

A diameter or fillet radius is formed by the shape of the cutting tool. The included angle may vary from 90° to 135°, with a maximum taper length of .400, depending on the type of lathe control and whether a rough or finish cut is made. Tapered diameters are generated on NC or tracer controlled lathes except for rough cuts where standard cutter tools can be used. There may be one or more cuts required depending on the amount of stock removed in each cutting pass. The parameters of the cut are specified below:

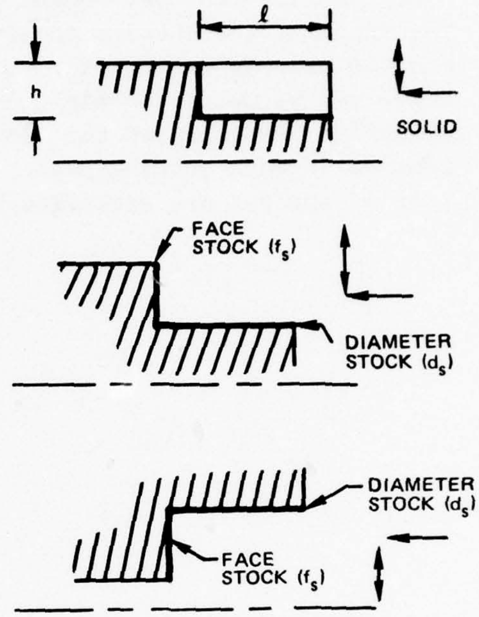




Type of Machine	Manual, Automatic, Semiautomatic		Numerical Control, Tracer Lathe	
Type of Cut	rough	finish	rough	finish
Included Angle	90-135	90-135	90, 105, 120, 135	90
Diameter length ($A = 90^{\circ}$)	≤.400	≤.100	≤.400	≤.100
Taper length ($A > 90^{\circ}$)	≤.400	≤.100	≤.400	N/A
Radius	≤.250	≤.125	≤.125	≤.125
ℓ/h	< 1.0	< 1.0	< 1.0	< 1.0

TURN AND FACE
BORE AND FACE

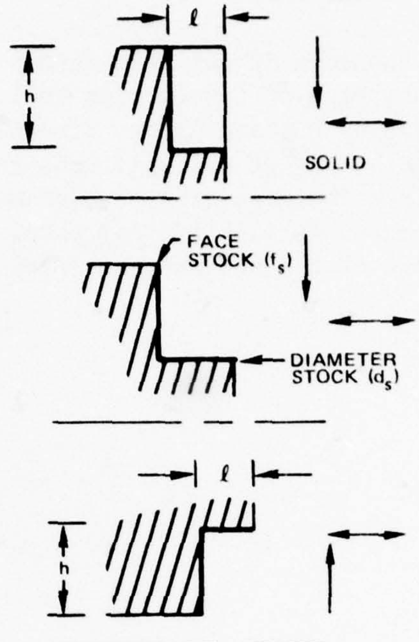
A shoulder is cut that cannot be formed by the shape of the cutting tool. The cut is made by cutting in two directions. There can be one or multiple cuts in either direction depending on the amount of stock removed in each cutting pass. The parameters of the cut are specified below:



Type of Machine	Manual, Automatic, Semiautomatic		Numerical Control, Tracer Lathe	
Type of Cut	rough	finish	rough	finish
Included Angle	90	90	90	90
Shoulder Height	>.400	>.100	>.400	>.100
Radius	≤.250	≤.125	≤.125	≤.125
ℓ/h (cut from solid)	≥1.0	≥1.0	≥1.0	≥1.0
ds/fs (not from solid)	≥1.0	≥1.0	≥1.0	≥1.0

FACE AND TURN
FACE AND BORE

A shoulder is cut that cannot be formed by the shape of the cutting tool. The cut must be made by cutting in two directions. There can be one or multiple cuts in either direction depending on the amount of stock removed in each cutting pass. The parameters of the cut are specified below:



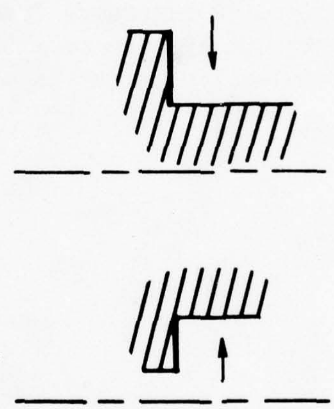
Type of Machine	Manual, Automatic, Semiautomatic		Numerical Control, Tracer Lathe	
Type of Cut	rough	finish	rough	finish
Included Angle	90	90	90	90
Diameter Length	>.400	>.100	>.400	>.100
Radius	≤.250	≤.125	≤.125	≤.125
ℓ/h (from solid)	<1.0	<1.0	<1.0	<1.0
ds/fs (not from solid)	<1.0	<1.0	<1.0	<1.0

TURN AND CLEAR SHOULDER
BORE AND CLEAR SHOULDER OR END OF BORE

A diameter is cut with the requirement to feed the cutting tool up to, but clearing, the surface of a shoulder. Outside diameters will be cut with a turning tool, and inside diameters with a boring tool. There may be one or multiple cuts required depending on the amount of stock removed in each cutting pass.

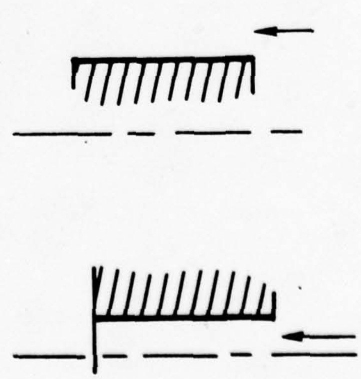
FACE AND CLEAR DIAMETER

A face is cut with the requirement to feed the cutting tool into, but clearing, the adjacent diameter or tapered surface. The face cut can be internal or external to the part, can be a "back" face, groove face or any exposed face. There may be one or multiple cuts required depending on the amount of stock removed in each cutting pass.



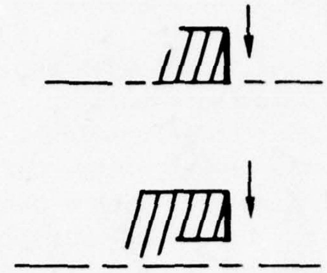
TURN OPEN DIAMETER
BORE OPEN DIAMETER

An open diameter is cut permitting a thru cutting operation. Outside diameters are cut with a turning tool and inside diameters with a boring tool. There may be one or multiple cuts required depending on the amount of stock removed in each cutting pass.



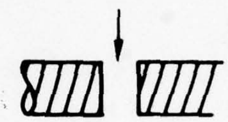
FACE OPEN

An open face or end of a part is cut permitting a thru cutting operation. The face cut can be internal or external to the part. There may be one or more multiple cuts required depending on the amount of stock removed in each cutting pass.



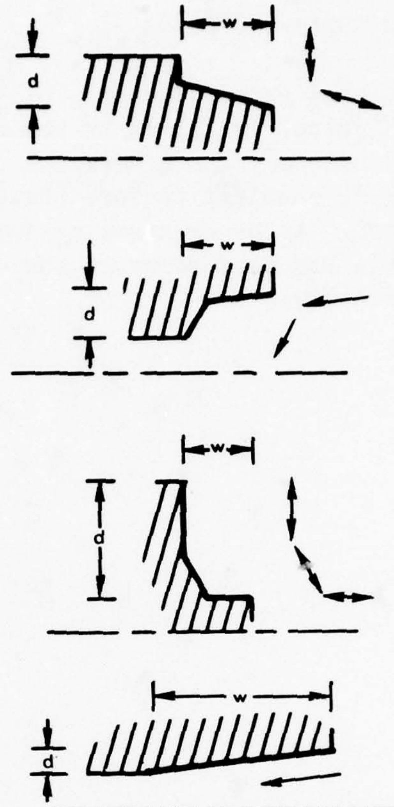
CUTOFF

The workpiece is separated from the bar stock. The cut applies only to bar machines and only one cut is made.



GENERATE CONTOUR

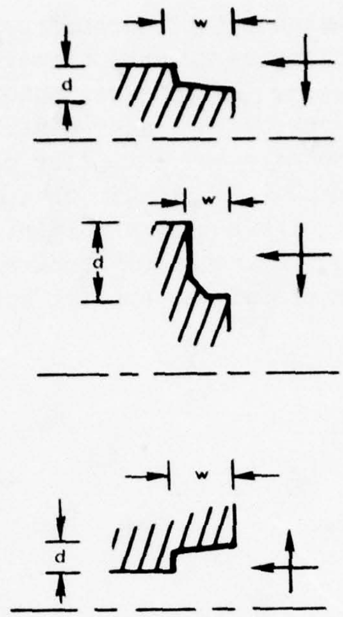
At least one tapered surface is cut or a fillet radius greater than .125 is generated. A numerical controlled lathe or a lathe with tracer control must be used to make the cut. The cut is not made on a manual, automatic or semiautomatic lathe. There can be multiple cuts depending on the amount of stock removed. The parameters of the cut are specified below:



Type of Machine	Manual, Automatic, Semiautomatic		Numerical Control, Tracer Lathe	
Type of Cut	N/A	N/A	rough	finish
Width of Cut (w > d)	N/A	N/A	>.300	>.100
Depth of Cut (d > w)	N/A	N/A	>.300	>.100
Radius (no tapers)	N/A	N/A	>.125	>.125

FORM TAPERED CONTOUR

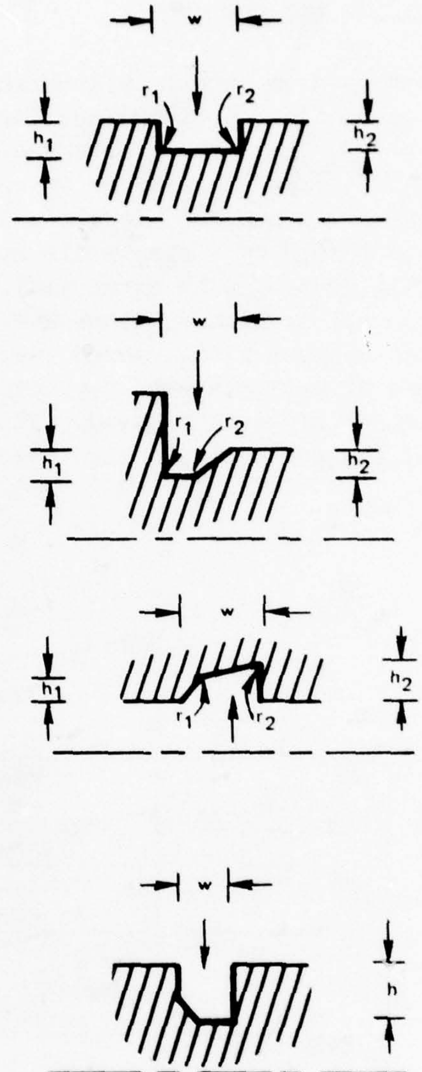
A contour consisting of a taper and located at a corner is formed by the shape of the cutting tool. In general, a specific tool will be required to form the contour. The contour can be external or internal to the part. The parameters of the cut are specified below:



Type of Machine	Manual, Automatic, Semiautomatic		Numerical Control, Tracer Lathe	
Type of Cut	rough	finish	rough	finish
Width of Cut ($w > d$)	≤ 1.0	$\leq .500$	$\leq .300$	$\leq .100$
Depth of Cut ($d \geq w$)	≤ 1.0	$\leq .500$	$\leq .300$	$\leq .100$

FORM GROOVE

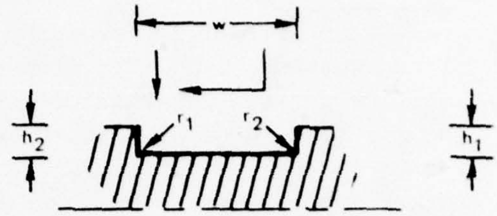
A groove or relief is formed by the shape of the cutting tool. The groove can be cut into any surface external or internal to the part. In general, grooves are always formed if they are within a specified width. Larger grooves are formed by several plunge cuts depending on the site of the groove's radii. When using numerical control or tracer lathes, the preference is to plunge and turn larger size grooves or grooves whose radii can be generated. The parameters of the cut are specified below:

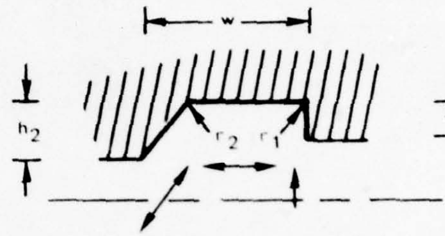


Type of Machine	Manual, Automatic, Semiautomatic		Numerical Control, Tracer Lathe	
Type of Cut	rough	finish	rough	finish
Condition A (surfaces ≥3)	$w \leq 1.0$	$w \leq .500$	$w \leq .500$	$w \leq .300$
Condition B (surfaces = 3)	$1.0 < w \leq 1.5$ $h_i > r_i$	$.500 < w \leq 1.50$ $h_i > r_i$	$.500 < w \leq 1.0$ r_1 or $r_2 \leq .200$	$.300 < w \leq .500$ $h_i > r_i$
Condition C (surfaces = 3)				$.300 < w \leq .500$ $r1$ or $r_2 \leq .050$
Condition D (surfaces = 3)				$.500 < w \leq 1.0$ $r_i \leq .050$

PLUNGE AND CUT GROOVE

A groove or recess is generated by a combination of plunge and turning or boring cuts. The groove can be cut into any surface external or internal to the part. In general, larger size grooves are not formed by a single direction plunge nor will grooves with large radii. Numerical control or tracer lathes must be used to cut grooves with tapered surfaces. There may be multiple cuts depending on the amount of stock removed. The parameters of the cut are specified below:

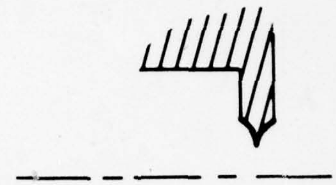




Type of Machine	Manual, Automatic, Semiautomatic		Numerical Control, Tracer Lathe	
Type of Cut	rough	finish	rough	finish
Condition A	$w > 1.5$ no tapers	$w > 1.5$ no tapers	$w > 1.0$	$w > 1.0$
Condition B (surfaces = 3)	$1.0 < w \leq 1.5$ r_1 or $r_2 > h_1$ or h_2 no tapers	$.500 < w \leq 1.50$ r_1 or $r_2 > h_1$ or h_2 no tapers	$.500 < w \leq 1.0$ $r_i > .200$	$.300 < w \leq .500$ $r_i > .050$ h_1 or $h_2 < r_1$ or r_2
Condition C (surfaces = 3)				$.500 < w \leq 1.0$ r_1 or $r_2 > .050$

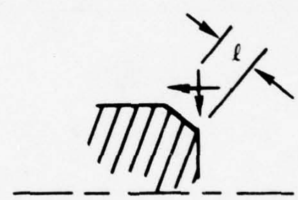
FORM FIN

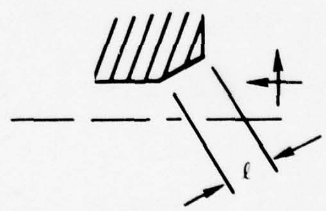
A particular kind of feature is formed by the shape of a special cutting tool. The feature can be cut into any flange external or internal to the part.



FORM CHAMFER

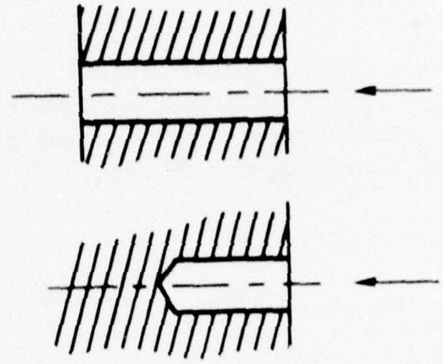
A chamfer is formed by the shape of the cutting tool. Chamfers are small tapers located at the corners of a part. The length of a formed chamfer must be .400 or less.





DRILL BORE

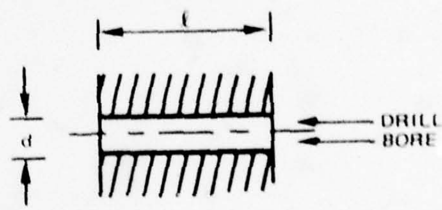
An internal diameter parallel to the center line is formed by cutting into or thru solid material. The parameters of the cut are:



	Machine	Type of Cut	Diameter	Tolerance	ℓ/d
Condition A	turret lathe	finish	.250 - .500	>.001	<1.0
Condition B	turret lathe	finish	>.500	>.001	N/A

DRILL BORE AND BORE

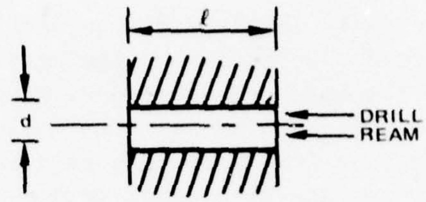
An internal diameter parallel to the center line is formed from solid by a final operation (i.e., the diameter is finish cut). The parameters of the cut are:



	Machine	Type of Cut	Diameter	Tolerance	ℓ/d
Condition A	turret lathe	finish	.250 - .500	≤.001	<1.0
Condition B	turret lathe	finish	>.500	≤.001	N/A

DRILL BORE AND REAM

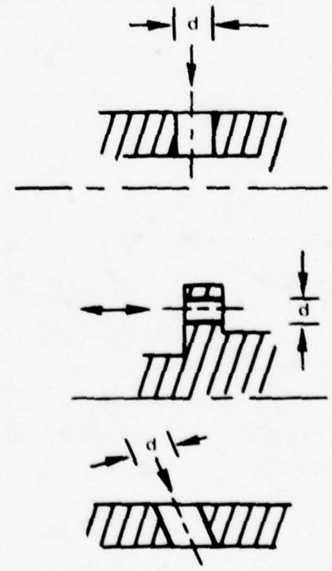
An internal diameter parallel to the center line is formed from solid by a final operation (i.e., the diameter is finish cut). The parameters of the cut are:



	Machine	Type of Cut	Diameter	Tolerance	ℓ/d
Condition A	turret lathe	finish	.250 - .500	≤.001	≥1.0
Condition B	turret lathe	finish	<.250	≤.001	N/A

DRILL HOLE

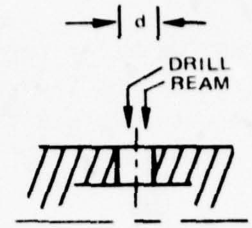
A radial, longitudinal or angular hole is formed. Depending on the size (diameter) of the hole and tolerance, holes may or may not require reaming. The following parameters are for holes that require only a drilling operation on a drill press:

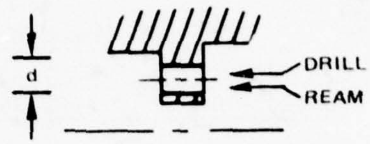


Condition	A	B	C	D	E
Diameter	< .125	.125 - .250	.250 - .500	.500 - 1.0	> 1.0
Tolerance	> .002	> .004	> .005	≥ .010	≥.015

DRILL HOLE AND REAM

A radial, longitudinal or angular hole is formed. Depending on the size (diameter) of the hole and tolerance, holes may or may not require reaming. The following parameters are for holes that require both drilling and reaming on a drill press:

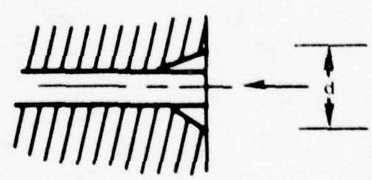




Condition	A	B	C	D	E
Diameter	<.125	.125 - .250	.250 - .500	.500 - 1.0	>1.0
Tolerance	≤.002	≤.004	≤.005	<.010	<.015

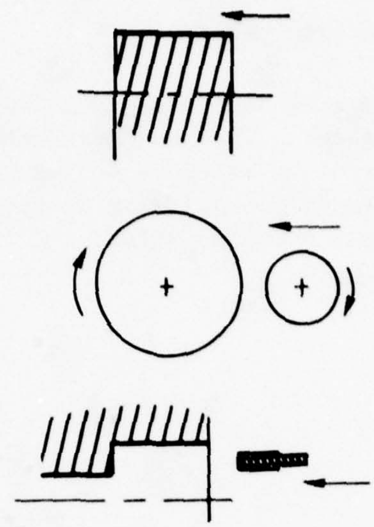
COUNTERSINK

A tapered surface or chamfer is formed at the opening of a bore or radial, longitudinal or angular hole. If the diameter of the bore is greater than 2.0, the cut is made with a chamfer tool instead of a countersink.



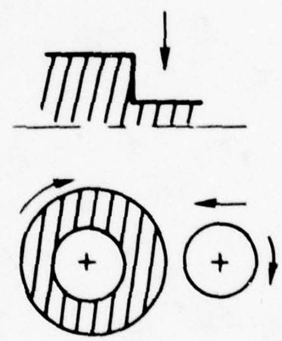
GRIND DIAMETER

An inside or outside diameter is ground. The diameter can be open on both ends or bounded on end by a shoulder. The requirement for grinding is specified by the process decision rules.



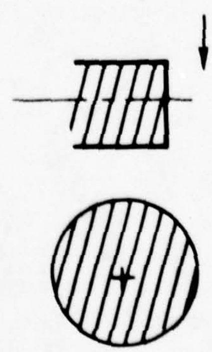
GRIND FACE

A face is ground. The face cut can be internal or external to the part. It can be the side of a groove. The requirement for grinding is specified by the process decision rules.



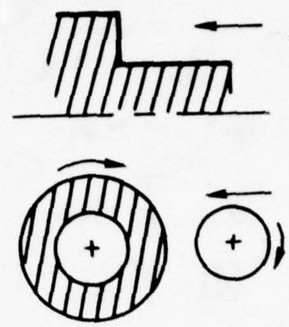
GRIND END

The end of the part is ground. The requirement for grinding is specified by the process decision rules.



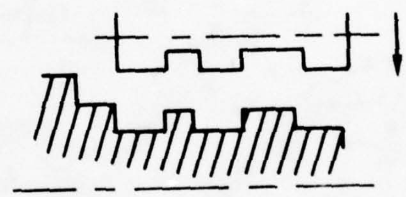
GRIND DIAMETER AND FACE

A diameter and face are ground in the same operation. The shoulder feature can be internal or external to the part. The requirement for grinding is specified by the process decision rules.



CRUSH GRIND

Recessed features (e.g., grooves) are ground into an outside diameter. The requirement for crush grinding is specified by the process decision rules.



HONE DIAMETER

An inside diameter is honed. The requirement for honing is specified by the process decision rules.

LAP DIAMETER

A diameter, internal or external to the part, is lapped. The requirement for lapping is specified by the process decision rules.

MILL FEATURE

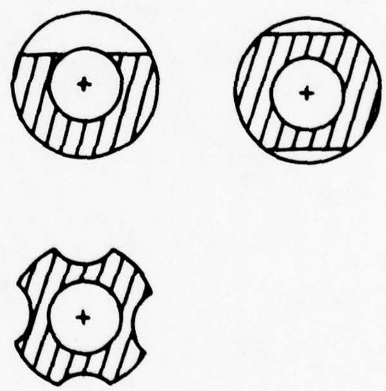
A feature (e.g., slots, flats, windows) is milled. The requirement for milling is specified by the process decision rules.

EDM FEATURE

A feature (window or hole) is cut by an EDM operation. The requirement for EDM is specified by the process decision rules.

SHAPE FEATURE

A particular type of feature (flat, slot, window, lug, tab) is cut into a diameter. The requirement for each type of cut is specified by the process decision rules.



TAP HOLES

A radial, longitudinal or angular hole is threaded.

APPENDIX H

DEFENSE BENEFITS DATA AND CALCULATIONS

Data and calculations generated in the analysis of defense benefits from CPPP are reported in this appendix. The contents, in order, are:

1. The survey sent to defense industry, with a compilation of responses. (The results of an earlier general industry survey are presented in the Interim Report, which is incorporated by reference into the Final Report.)

2. The CPPP description included in the defense industry survey.

3. The discounted cash flow analyses performed to estimate CPPP benefits to defense industry. Six analyses were conducted, treating the demonstration and enhanced CPPP capabilities for three model defense suppliers. For each case, three tables are given: inputs, results, and sensitivity analyses.

4. The analyses of CPPP impact on defense procurement costs. Six analyses are shown, projecting benefits of the demonstration and enhanced CPPP systems on Army missile procurement, overall Army procurement, and Department of Defense procurement.

R77-942625-14

IIT Research Institute
10 West 35 Street, Chicago, Illinois 60616
312/567-4000

Gentlemen:

The U. S. Army Missile Research and Development Command, under its Manufacturing Methods and Technology Program is sponsoring the development of a computerized production process planning (CPPP) system. The system will perform process planning of machined, cylindrical, metal parts. United Technologies Research Center, East Hartford, Connecticut, is the contractor for this development. A brief description of the CPPP system accompanies this letter.

One objective of the program is to project benefits of the system to industries producing Army missile components or other defense items. The IIT Research Institute (IITRI), Chicago, Illinois, has subcontracted for the majority of this task. In the attached data request, we are soliciting an estimate of the cost reduction potential of the CPPP system. Should you choose to respond, your estimate will be consolidated with those of other respondees and used in the benefit projection.

Your cooperation in the evaluation of this new technology would be very helpful and sincerely appreciated.

Cordially,

John D. Meyer

John D. Meyer, Group Leader
Industrial and Manufacturing
Engineering

JDM/mmo
Encs.

DATA REQUEST

The purpose of this data request is to collect some general information concerning your company and products, your current process planning procedures and your estimate of the impact the prototype process planning system would have on your manufacturing operation. All data will be considered proprietary and will be summarized or consolidated so that specific sources cannot be identified.

Please take a few minutes to read each question carefully before answering it. If the information we request is not readily available or you are unable to obtain it, please give us the best estimate you can.

In order to complete our study within the allotted time, we request that you complete this form and return it by April 15, 1977.

If you have any questions or need additional information, please feel free to call (collect) Mr. John Meyer at 312/567-4609.

---

1. Does your plant produce products which are used in any of the following?

	Yes	No
U.S. Army Missiles and Rockets	5	8
Other U.S. Army Equipment	3	10
Other Dept. of Defense Equipment	13	0

NUMBER OF RESPONSES ARE SHOWN IN EACH BOX

2. What is the approximate dollar value of all machined, cylindrical, metal parts manufactured in your plant annually? (By cylindrical parts, we mean those which are symmetrical about an axis of rotation and the primary manufacturing operations are turning, boring, etc.)

$__________

- - - - - - - - - - - - - - - -

NUMBER OF RESPONSES = 10
AVERAGE = \$5,193K
STANDARD DEVIATION = \$9,669K
RANGE = \$4K to \$30,000K

- - - - - - - - - - - - - - - -

3. Approximately how much does your plant spend annually for preparing or modifying process plans for machined, cylindrical, metal parts? (This should also include process planning costs for make/buy studies, cost estimates, etc., if appropriate.)

$__________

- - - - - - - - - - - - - - -

NUMBER OF RESPONSES = 10
AVERAGE = \$168K
STANDARD DEVIATION = \$139K
RANGE = \$9K to \$371K

- - - - - - - - - - - - - - -

4. Is your plant currently using any form of computer assisted process planning for machined, cylindrical metal parts?

Yes	No
3	10

5. Is your plant currently using any form of computer assisted process planning for other parts or assemblies?

Yes	No
8	5

PLEASE READ THE ENCLOSED DESCRIPTION OF THE PROCESS PLANNING SYSTEM BEING DEVELOPED BY UNITED TECHNOLOGIES RESEARCH CENTER BEFORE ANSWERING THE FOLLOWING QUESTIONS.

6. Assuming such a system was operational in your plant, what would be the approximate percentage change in the overall cost of manufacturing a typical machined, cylindrical, metal part over one planned manually? (Changes in process planning costs, including recurring computer charges, and the costs of tooling, direct labor, material, scrap and rework, and overhead, should be considered. Please exclude the costs of installing and maintaining the system in your estimate.)

Plus or Minus (circle one) _______________%

- - - - - - - - - - - - - -

NUMBER OF RESPONSES = 13
AVERAGE = -9.4%
STANDARD DEVIATION = 8.6%
RANGE = -25% to +10%

- - - - - - - - - - - - - -

7. What would be the percentage change in process planning costs for machined, cylindrical, metal parts if such a system were used instead of manual process planning?

Plus or Minus (circle one) _______________%

- - - - - - - - - - - - - - -

NUMBER OF RESPONSES = 13
AVERAGE = -37.5%
STANDARD DEVIATION = 18.7%
RANGE = -60% to +25%

- - - - - - - - - - - - - - -

8. Assuming that reliable software, good user documentation, and a training source were available, and that the system was given to you free of charge, what do you feel would be a realistic cost and time for your company to install such a system? (This should include establishing initial data files, training of personnel, testing the system, etc. It should exclude costs of computer hardware.)

$____________

________ Months

- -
NUMBER OF RESPONSES = 11
AVERAGES = $162K, 10.4 Months
STANDARD DEVIATIONS = $204K, 4.4 Months
RANGES = $10K to $300K, 4.5 to 18 Months
- -

9. If additional computer hardware would be required to install the system in your plant, please estimate its cost.

$____________

- - - - - - - - - - - - - - -
NUMBER OF RESPONSES = 12
AVERAGE = $116K
STANDARD DEVIATION = $151K
RANGE = $0 to $500K
- - - - - - - - - - - - - - -

10. What would be the approximate annual costs for maintaining such a system? (This should include costs for program maintenance and updating of data files.)

$____________

- - - - - - - - - - - - - - -
NUMBER OF RESPONSES = 12
AVERAGE = $50.2K
STANDARD DEVIATION = $41.2K
RANGE = $8K to $120K
- - - - - - - - - - - - - - -

11. Considering the answers you gave to questions 8, 9, and 10, what percentage (by dollar value) of the *machined*, cylindrical, metal parts you manufacture in-house would benefit from the system each year, starting from the time you made the decision to install the system?

YEAR	1	2	3	4	5	6	7	8	9	10
PARTS IMPACTED (%)										

NUMBER OF RESPONSES = 11

YEAR	1	2	3	4	5	6	7	8	9	10
MINIMUM (%)	0.1	0.5	1	5	10	10	10	10	10	10
MAXIMUM (%)	40	80	100	100	100	100	100	100	100	100
AVERAGE (%)	13	34	52	64	70	72	75	76	78	79

12. Please place a check-mark in front of those items which you feel would be major advantages of this computer aided process planning system.

*

9 Reduced Manufacturing Costs

10 Reduced Production Leadtime

6 Increased Machine Utilization

5 Improved Product Quality

6 Increased Direct Labor Utilization

12 More Uniform Process Plans

7 Improved Cost Estimating Procedures

3 Better Make/Buy Decisions

* Number of responses

3 Increased Product Standardization

5 Reduced Critical Labor Skills

1 Improved Raw Material Standardization

3 Improved Producibility of Parts

2 Better Plant Layout

3 Better Material Handling

8 Improved Production Scheduling

6 Improved Capacity Planning

1 Others (Please Specify) Better Tool Usage

13. Please place a check-mark in front of those items which you feel would be major obstacles or disadvantages to implementing the system.

*

10 Economic Justification

7 Management Commitment

1 Training of Personnel

2 Lack of Qualified Computer Analysts

5 User Acceptance of the System

7 Interfacing with Existing Systems

10 Establishing Initial Data Bases for Machines, Tooling and Process Decision Rules

7 Getting the System Debugged and Operational

3 Insuring Quality of Input Data

3 Maintenance of the Data Bases

7 System Complexity and Reliability

0 Others (Please Specify) ______

* Number of responses

14. Other Comments?

(1) Would not implement system unless all machined and fabricated parts were included.

15. Name ______

Title ______

Organization ______

Address ______

Phone ______

Thank you for your cooperation. It is sincerely appreciated. Please return this form in the attached, self-addressed envelope to:

Mr. John D. Meyer
Management & Computer Sciences Division
IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616

COMPUTERIZED PRODUCTION PROCESS PLANNING (CPPP)

CPPP provides a computer capability for process planning of machined, cylindrical, metal parts. The equivalent of a fully detailed blueprint is input to the system. The process plan documentation output by CPPP consists of a summary of operations and an operation sheet for each operation. The operation sheet contains a dimensioned sketch and shows cuts to be made, tools, feeds, speeds, and other data.

The system generates the sequence of metalcutting and non-metalcutting operations required to manufacture a part. It selects machine tools and determines the types of cuts to be made in an operation. Planning data such as tools, feeds, and speeds can be determined in some situations, but these will usually be added by the process planner in this initial version of the system. It may also be necessary to modify CPPP-calculated dimensions in certain cases.

Data Base

CPPP uses a large manufacturing data base. Files containing part and raw material specifications, machine tool data, cutting tool data, and machinability data are required. The data base also holds process rules which determine sequences of operations and can be applied to select types of cutting tools for specific cutting situations. These rules are formulated in an English-like process planning language developed for CPPP (Figure 1). Because manufacturing rules are included in the data base rather than in CPPP programming, the system is independent of local manufacturing practice. Each workshop can place its own manufacturing rationale in its data base.

Alternative Modes of Operation

A process planner operates CPPP from a graphic computer terminal. Three modes of operation are available: automatic, semi-automatic, and interactive. In the automatic mode, CPPP uses stored process rules to generate a process plan without human supervision. Process rules are also used in semi-automatic operation, but the process planner may review and modify CPPP decisions as they are made. (Figure 2 shows the terminal display at one review/modification point.) In the interactive mode, the sequence of operations is specified by the process planner in a dialog with CPPP. The system is then used to produce detailed operation plans. In both the semi-automatic and interactive modes, the process planner can choose varying levels of overseeing CPPP by specifying which decisions he wishes to review and which he will accept. He can also use these modes to enter new data (e.g., tools, machines, feeds, speeds) into the system.

CPPP Processing

Figure 3 gives an overview of CPPP process planning. The process planner initiates a CPPP session by specifying part number, lot size, mode of operation, and other data. CPPP retrieves from the data base the part design, workpiece description and, if desired, process rules for the part's family.

The first CPPP planning step is generation of a sequence of operations. This is done using process rules or through interaction between the system and the process planner. Operations are defined in turn by specifying operation type, the type of machine tool to be used, and the part surfaces to be affected. Non-metalcutting operations (plating, heat treatment, deburring, inspection, etc.) may be generated as well as metalcutting ones.

Once the sequence of operations is complete, each operation is planned in detail. The procedure below is used for metalcutting operations. Decision-making is based on economic analysis of cost and/or production rate.

1. Identify candidate machine tools.
2. Select candidate cut sequences for each machine.
3. Identify candidate cutter tools for each cut in each sequence.
4. Determine cut parameters (feed, speed, time, tool life, etc.) for each cut and tool. These determinations are made using machining recommendations rather than by optimizing mathematical models.
5. Choose the best tools for each cut sequence.
6. Choose the best sequence for each machine.
7. Choose the best machine.

No economic analysis is performed for non-metalcutting operations.

After all operations have been planned in detail, dimensions and tolerances are calculated backward from the last operation to the first. For each operation, tolerances are determined, stock removal calculated, and workpiece dimensions previous to the operation are established.

The completed process plan can be reviewed and modified at the terminal. A summary of operations and detailed operation sheets can be requested.

Areas of Possible Savings

CPPP has, or may have, cost reduction potential in the following areas:

1. Process planning labor and lead time.

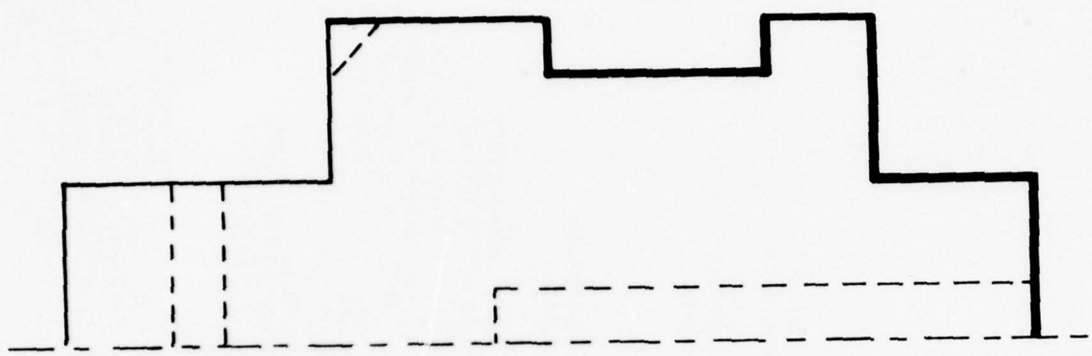
2. Reduced tooling inventory due to standardized tool selection
3. Benefits resulting from the use of standardized rules to generate sequences of operations
4. Reduction in machining costs due to the economic analysis of alternative cutting tools, cut sequences, and machine tools.

```
0010    DRAW MATERIAL AT MC0100 (BENCH)  $
0020    ORIENT PART FOR LONGEST OD SETUP  $
0030    TURN OUTSIDE SURFACE ON MC3500 (AUTOMATIC BAR MACHINE) IN NORMAL IF
             SURFACE IS AN END (OR)
             FEATURE IS A SEMIOPEN DIAMETER,
              FEATURE IS EXPOSED (OR)
             FEATURE IS AN OPEN DIAMETER,
              FEATURE IS EXPOSED (AND)
          PROVIDING THE FOLLOWING CONDITIONS ARE SATISFIED:
             RESULTING DIAMETER SEPARATION (0.040),
             RESULTING LONGEST DIAMETER (0.025)  $
0040    HEAT TREAT IN MC1300 (FURNACE), MT2700 (FURNACE 2700) TO SPECIFIED HARDNESS PER
         PMP510  $
0050    GRIND THE LONGEST OD ON MC2500 (CENTERLESS GRINDER)  $
0060    DRILL THE THRU BORE WITH MC3100 (GUN DRILL) IF
             DIAMETER IS .LE 0.787  $
0070    DRILL THE THRU BORE WITH MC3200 (EJECTOR DRILL) IF
             DIAMETER IS .GT 0.787  $
0080    TURN OUTSIDE SURFACE ON MC3600 (AUTOMATIC CHUCKER) OR MC9300 (NC LATHE) IN
         REVERSE IF
             SURFACE IS A FREE END (OR)
             FEATURE IS A SEMIOPEN DIAMETER,
              FEATURE IS NOT CUT,
              FEATURE IS EXPOSED (OR)
             FEATURE IS AN OPEN DIAMETER,
              FEATURE IS NOT CUT,
              FEATURE IS EXPOSED (OR)
             FEATURE IS A RELIEF (OR)
             SURFACE IS LARGEST OD BACKFACE,
              SURFACE IS NOT A RELIEF FACE,
              LATERAL TOLERANCE IS .GE .005  $
0080C   TURN INSIDE SURFACE IF
             FEATURE IS A COUNTERBORE,
              FEATURE IS EXPOSED,
              FEATURE IS NOT A SHARP EDGE FEATURE (OR)
             FEATURE IS A RELIEF (OR)
             FEATURE IS A GROOVE,
              FEATURE IS EXPOSED
              FEATURE IS A COUNTERBORE
              FEATURE LOCATION IS .LE 0.5*PART LENGTH  $
0090    HAND REAM THE THRU BORE ON MC5300 (BENCH LAP) IF
             DIAMETER IS .LT 0.375  $
0100    HONE THE THRU BORE WITH MC2830 (AUTOMATIC HONE) IN NORMAL  $
```

Figure 1. Process rules for generating sequence of operations. These rules are compiled by the CPPP language processor. The compiled form of the rules is stored in the data base and used in process planning.

UTRC CPPP SYSTEM. ACCEPT/MODIFY GENERATED OPERATION.

OP 0030 DESCRIPTION: TURN
MACH. CLASS 1: 0300 LATHE
MACH. CLASS 2: (NONE)



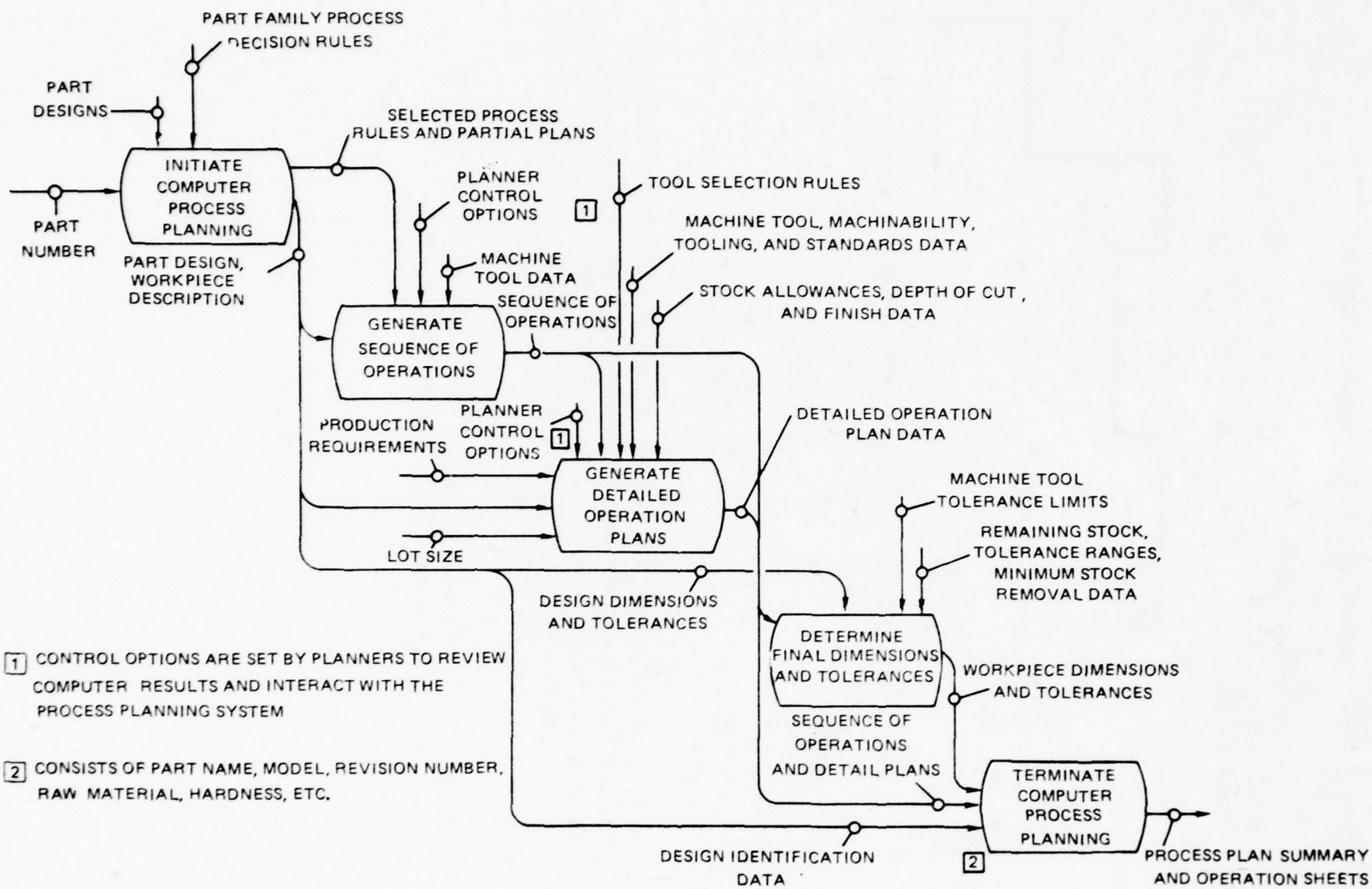
EDHFCDG FDEDF
00000000000000
00000000011111
12345678901234
XXXXXXX

TYPE C/R TO ACCEPT OPERATION OR TYPE AN OPTION AND THE REQUIRED DATA:
1 NEW DESCRIPTION 2 MACHINE CLASS NUMBER (1 OR 2), CODE, NAME
3 MACHINE TOOL CODE, NAME 4 LIST OF ADDED CUTS 5 LIST OF DELETED
CUTS 6 (CHANGES SETUP) 7 (DELETES OPERATION) 8 (SHOWS MACHINE
DATA) 9 (TERMINATES PLANNING)

Figure 2. Terminal display at one of the optional points offered for review/modification of CPPP decisions.

FIGURE 3 OVERVIEW OF CPPP PROCESSING

IN THIS STRUCTURED DIAGRAM, MAJOR CPPP FUNCTIONS ARE SHOWN IN BOXES. INPUT AND CONTROL DATA FOR A FUNCTION ARE SHOWN BY ARROWS ENTERING BOXES FROM LEFT AND ABOVE, RESPECTIVELY. OUTPUTS ARE INDICATED BY ARROWS EXITING FROM RIGHT



[1] CONTROL OPTIONS ARE SET BY PLANNERS TO REVIEW COMPUTER RESULTS AND INTERACT WITH THE PROCESS PLANNING SYSTEM

[2] CONSISTS OF PART NAME, MODEL, REVISION NUMBER, RAW MATERIAL, HARDNESS, ETC.

ANNUAL VALUE OF PARTS ($K) = 50000.0   ANNUAL VALUE OF WIPI ($K) = 25000.0

CURRENT COST COMPONENTS....

PROCESS PLANNING	= 3.0%	TOOLING	= 5.0%
DIRECT LABOR	= 25.0%	MATERIAL	= 20.0%
SCRAP & REWORK	= 2.0%	OVERHEAD, FEE, ETC	= 45.0%

POTENTIAL SAVINGS FOR THIS CASE....

PROCESS PLANNING	= 40.0%	TOOLING	= 5.0%
DIRECT LABOR	= 5.0%	MATERIAL	= 3.0%
SCRAP & REWORK	= 6.0%	WIPI	= 4.0%

YEARLY INPUT....

YEAR	1	2	3	4	5	6	7	8	9	10
HARDWARE COSTS ($K)	35.0	20.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ESTABLISH DATA FILES ($K)	40.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRAIN PERSONNEL ($K)	12.0	12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TEST SYSTEM ($K)	20.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COMPUTER CHARGES & MAINTENANCE ($K)	0.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0
UPDATE DATA FILES ($K)	0.0	22.5	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
PERCENT OF PARTS IMPACTED (%) (BY DOLLAR VALUE)	0.0	10.0	25.0	40.0	65.0	90.0	90.0	90.0	90.0	90.0

TABLE H1. INPUT DATA FOR CASH FLOW ANALYSIS -- INPACT OF DEMONSTRATION CPPP ON LARGE COMPANY WITH HIGH PART SIMILARITY.

YEAR	HARDWARE ($K)	ESTABLISH DATA FILES ($K)	TRAIN PERSONNEL ($K)	TEST SYSTEM ($K)	COMPUTER CHARGES & PROGRAM MAINTENANCE ($K)	UPDATING DATA FILES ($K)	PERCENTAGE OF PARTS IMPACTED (%)	PROCESS PLANNING SAVINGS ($K)	TOOLING SAVINGS ($K)	DIRECT LABOR SAVINGS ($K)	MATERIAL SAVINGS ($K)	SCRAP & REWORK COST SAVINGS ($K)	WIPI SAVINGS ($K)	DEPRECIATION ($K)	INVESTMENT TAX CREDIT ($K)	CASH FLOW BEFORE TAXES & DEPRECIATION ($K)	CASH FLOW AFTER TAXES & DEPRECIATION ($K)	CUMULATIVE PRESENT VALUE AFTER TAXES & DEPRECIATION ($K)
1	33.	40.	12.	20.	0.	0.	0.	0.	0.	0.	0.	0.	0.	6.	2.	-107.	-67.	-64.
2	20.	40.	12.	20.	73.	22.	10.	60.	12.	62.	30.	6.	30.	9.	1.	11.	2.	-62.
3	10.	0.	0.	0.	73.	43.	23.	130.	31.	136.	73.	13.	73.	10.	1.	372.	194.	91.
4	0.	0.	0.	0.	73.	43.	40.	240.	50.	250.	120.	24.	120.	9.	0.	684.	360.	349.
5	0.	0.	0.	0.	73.	43.	63.	390.	81.	406.	193.	39.	193.	8.	0.	1186.	621.	734.
6	0.	0.	0.	0.	73.	43.	90.	340.	112.	362.	270.	34.	270.	7.	0.	1689.	881.	1273.
7	0.	0.	0.	0.	73.	43.	90.	340.	112.	362.	270.	34.	270.	5.	0.	1689.	881.	1749.
8	0.	0.	0.	0.	73.	43.	90.	340.	112.	362.	270.	34.	270.	4.	0.	1689.	880.	2180.
9	0.	0.	0.	0.	73.	43.	90.	340.	112.	362.	270.	34.	270.	3.	0.	1689.	880.	2572.
10	0.	0.	0.	0.	73.	43.	90.	340.	112.	362.	270.	34.	270.	2.	0.	1689.	879.	2927.
TOTALS	63.	80.	24.	40.	673.	332.		3349.	737.	3687.	1770.	334.	1770.	64.	3.	10592.	3312.	

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 7.37
YEARS TO PAYBACK = 2.4
RETURN ON INVESTMENT = 170.4

FOR 10% ANNUAL DISCOUNT FACTOR BEFORETAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 7.80
YEARS TO PAYBACK = 2.4
RETURN ON INVESTMENT = 188.8

TABLE H2. CASH FLOW ANALYSIS -- IMPACT OF DEMONSTRATION CPPP ON LARGE COMPANY WITH HIGH PART SIMILARITY

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 7.37
YEARS TO PAYBACK = 2.4
RETURN ON INVESTMENT = 170.4

		.. NET CHANGES IN ...		
	CHANGE	BCR	YTP	ROI
	******	*****	*****	*****
PERCENT OF PARTS IMPACTED	-10%	-0.73	0.13	-13.53
	10%	0.73	-0.10	13.23
PERCENT PROCESS PLANNING SAVINGS..................................	-10%	-0.22	0.04	-4.76
	10%	0.22	-0.03	4.44
PERCENT TOOLING SAVINGS	-10%	-0.03	0.01	-0.93
	10%	0.03	-0.01	0.93
PERCENT LABOR SAVINGS	-10%	-0.23	0.04	-4.76
	10%	0.23	-0.03	4.76
PERCENT MATERIAL SAVINGS..	-10%	-0.11	0.02	-2.34
	10%	0.11	-0.02	2.22
PERCENT SCRAP & REWORK SAVINGS....................................	-10%	-0.02	0.00	-0.63
	10%	0.02	-0.00	0.32
PERCENT WIPI SAVINGS..	-10%	-0.11	0.02	-2.34
	10%	0.11	-0.02	2.22
IMPLEMENTATION COSTS (HARDWARE, ESTABLISH FILES, TEST, TRAIN)	-10%	0.29	-0.07	12.06
	10%	-0.19	0.07	-10.47
RECURRING COSTS (COMPUTER CHARGES, MAINTENANCE, UPDATING FILES) ..	-10%	0.38	-0.04	4.13
	10%	-0.30	0.04	-4.13
VALUE OF MACHINED PARTS	-10%	-0.62	0.11	-13.33
	10%	0.62	-0.09	13.01
VALUE OF WIPI	-10%	-0.11	0.02	-2.34
	10%	0.11	-0.02	2.22
ORIGINAL PERCENT PROCESS PLANNING COSTS	-10%	-0.21	0.03	-4.44
	10%	0.21	-0.03	4.13
ORIGINAL PERCENT TOOLING COSTS....................................	-10%	-0.02	0.00	-0.32
	10%	0.02	-0.00	0.32
ORIGINAL PERCENT LABOR COSTS......................................	-10%	-0.10	0.02	-2.22
	10%	0.10	-0.01	1.90
ORIGINAL PERCENT MATERIAL COSTS	-10%	0.02	-0.00	0.32
	10%	-0.02	0.00	-0.63
ORIGINAL PERCENT SCRAP AND REWORK COSTS	-10%	-0.01	0.00	-0.32
	10%	0.01	-0.00	0.00
ORIGINAL OTHER OTHER COSTS (OVERHEAD, FEE, ETC.)..................	-10%	0.31	-0.07	10.47
	10%	-0.31	0.09	-10.79

TABLE H3. SENSITIVITY ANALYSIS -- IMPACT OF DEMONSTRATION CPPP ON LARGE COMPANY WITH HIGH PART SIMILARITY

ANNUAL VALUE OF PARTS ($K) = 50000.0   ANNUAL VALUE OF WIPI ($K) = 25000.0

CURRENT COST COMPONENTS....

PROCESS PLANNING	= 3.0%	TOOLING	= 5.0%
DIRECT LABOR	= 25.0%	MATERIAL	= 20.0%
SCRAP & REWORK	= 2.0%	OVERHEAD, FEE, ETC	= 45.0%

POTENTIAL SAVINGS FOR THIS CASE....

PROCESS PLANNING	= 80.0%	TOOLING	= 15.0%
DIRECT LABOR	= 10.0%	MATERIAL	= 5.0%
SCRAP & REWORK	= 10.0%	WIPI	= 4.0%

YEARLY INPUT....

YEAR	1	2	3	4	5	6	7	8	9	10
HARDWARE COSTS ($K)	35.0	20.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ESTABLISH DATA FILES ($K)	80.0	100.0	80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRAIN PERSONNEL ($K)	40.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TEST SYSTEM ($K)	0.0	30.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COMPUTER CHARGES & MAINTENANCE ($K)	0.0	135.0	135.0	135.0	135.0	135.0	135.0	135.0	135.0	135.0
UPDATE DATA FILES ($K)	0.0	60.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0
PERCENT OF PARTS IMPACTED (%) (BY DOLLAR VALUE)	0.0	5.0	20.0	35.0	60.0	80.0	90.0	90.0	90.0	90.0

TABLE H4. INPUT DATA FOR CASH FLOW ANALYSIS -- IMPACT OF ADVANCED CPPP ON LARGE COMPANY WITH HIGH PART SIMILARITY

YEAR	HARDWARE ($K)	ESTABLISH DATA FILES ($K)	TRAIN PERSONNEL ($K)	TEST SYSTEM ($K)	COMPUTER CHARGES & PROGRAM MAINTENANCE ($K)	UPDATING DATA FILES ($K)	PERCENTAGE OF PARTS IMPACTED (%)	PROCESS PLANNING SAVINGS ($K)	TOOLING SAVINGS ($K)	DIRECT LABOR SAVINGS ($K)	MATERIAL SAVINGS ($K)	SCRAP & REWORK COST SAVINGS ($K)	WIPI SAVINGS ($K)	DEPRECIATION ($K)	INVESTMENT TAX CREDIT ($K)	CASH FLOW BEFORE TAXES & DEPRECIATION ($K)	CASH FLOW AFTER TAXES & DEPRECIATION ($K)	CUMULATIVE PRESENT VALUE AFTER TAXES & DEPRECIATION ($K)
1	33.	80.	40.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	6.	2.	-133.	-92.	-88.
2	20.	100.	40.	30.	133.	60.	3.	60.	19.	62.	13.	3.	13.	9.	1.	-209.	-112.	-183.
3	10.	80.	0.	20.	133.	90.	20.	240.	73.	230.	60.	20.	60.	10.	1.	370.	193.	-33.
4	0.	0.	0.	0.	133.	90.	33.	420.	131.	437.	103.	33.	103.	9.	0.	1009.	329.	346.
5	0.	0.	0.	0.	133.	90.	60.	720.	225.	730.	180.	60.	180.	8.	0.	1890.	987.	989.
6	0.	0.	0.	0.	133.	90.	80.	960.	300.	1000.	240.	80.	240.	7.	0.	2593.	1333.	1789.
7	0.	0.	0.	0.	133.	90.	90.	1080.	337.	1125.	270.	90.	270.	5.	0.	2947.	1333.	2616.
8	0.	0.	0.	0.	133.	90.	90.	1080.	337.	1125.	270.	90.	270.	4.	0.	2947.	1333.	3367.
9	0.	0.	0.	0.	133.	90.	90.	1080.	337.	1125.	270.	90.	270.	3.	0.	2947.	1334.	4049.
10	0.	0.	0.	0.	133.	90.	90.	1080.	337.	1125.	270.	90.	270.	2.	0.	2947.	1334.	4669.
TOTALS	63.	260.	80.	30.	1213.	780.		6720.	2100.	7000.	1680.	360.	1680.	64.	3.	17290.	8995.	

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 6.40
YEARS TO PAYBACK = 3.1
RETURN ON INVESTMENT = 136.3

FOR 10% ANNUAL DISCOUNT FACTOR BEFORETAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 6.38
YEARS TO PAYBACK = 3.1
RETURN ON INVESTMENT = 143.1

TABLE H5. CASH FLOW ANALYSIS -- IMPACT OF ADVANCED CPPP ON LARGE COMPANY WITH HIGH PART SIMILARITY

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 6.40
YEARS TO PAYBACK = 3.1
RETURN ON INVESTMENT = 136.3

	CHANGE	.. NET CHANGES IN ... BCR	YTP	ROI
	******	*****	*****	*****
PERCENT OF PARTS IMPACTED	-10%	-0.64	0.12	-11.74
	10%	0.64	-0.11	11.43
PERCENT PROCESS PLANNING SAVINGS.................................	-10%	-0.22	0.04	-4.13
	10%	0.22	-0.04	3.81
PERCENT TOOLING SAVINGS	-10%	-0.07	0.01	-1.27
	10%	0.07	-0.01	1.11
PERCENT LABOR SAVINGS	-10%	-0.23	0.04	-4.13
	10%	0.23	-0.04	3.97
PERCENT MATERIAL SAVINGS...	-10%	-0.03	0.01	-1.11
	10%	0.03	-0.01	0.93
PERCENT SCRAP & REWORK SAVINGS....................................	-10%	-0.02	0.00	-0.48
	10%	0.02	-0.00	0.32
PERCENT WIPI SAVINGS..	-10%	-0.03	0.01	-1.11
	10%	0.03	-0.01	0.93
IMPLEMENTATION COSTS (HARDWARE, ESTABLISH FILES, TEST, TRAIN)	-10%	0.18	-0.06	7.93
	10%	-0.17	0.06	-6.98
RECURRING COSTS (COMPUTER CHARGES, MAINTENANCE, UPDATING FILES) ..	-10%	0.50	-0.03	4.13
	10%	-0.43	0.03	-4.13
VALUE OF MACHINED PARTS	-10%	-0.38	0.11	-10.79
	10%	0.38	-0.09	10.47
VALUE OF WIPI	-10%	-0.03	0.01	-1.11
	10%	0.03	-0.01	0.93
ORIGINAL PERCENT PROCESS PLANNING COSTS	-10%	-0.21	0.04	-3.81
	10%	0.21	-0.03	3.49
ORIGINAL PERCENT TOOLING COSTS....................................	-10%	-0.04	0.01	-0.93
	10%	0.04	-0.01	0.63
ORIGINAL PERCENT LABOR COSTS......................................	-10%	-0.11	0.02	-2.06
	10%	0.11	-0.02	1.90
ORIGINAL PERCENT MATERIAL COSTS	-10%	0.08	-0.01	1.27
	10%	-0.08	0.01	-1.39
ORIGINAL PERCENT SCRAP AND REWORK COSTS	-10%	-0.01	0.00	-0.32
	10%	0.01	-0.00	0.09
ORIGINAL OTHER OTHER COSTS (OVERHEAD, FEE, ETC.)...................	-10%	0.48	-0.07	8.37
	10%	-0.48	0.09	-8.89

TABLE H6. SENSITIVITY ANALYSIS -- IMPACT OF ADVANCED CPPP ON LARGE COMPANY WITH HIGH PART SIMILARITY

ANNUAL VALUE OF PARTS ($K) = 10000.0   ANNUAL VALUE OF WIPI ($K) = 6000.0

CURRENT COST COMPONENTS....

PROCESS PLANNING	= 5.0%	TOOLING	= 7.0%
DIRECT LABOR	= 20.0%	MATERIAL	= 15.0%
SCRAP & REWORK	= 3.0%	OVERHEAD, FEE, ETC	= 50.0%

POTENTIAL SAVINGS FOR THIS CASE....

PROCESS PLANNING	= 40.0%	TOOLING	= 5.0%
DIRECT LABOR	= 5.0%	MATERIAL	= 3.0%
SCRAP & REWORK	= 6.0%	WIPI	= 4.0%

YEARLY INPUT....

YEAR	1	2	3	4	5	6	7	8	9	10
HARDWARE COSTS ($K)	35.0	10.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ESTABLISH DATA FILES ($K)	30.0	30.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRAIN PERSONNEL ($K)	6.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TEST SYSTEM ($K)	10.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COMPUTER CHARGES & MAINTENANCE ($K)	0.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
UPDATE DATA FILES ($K)	0.0	18.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
PERCENT OF PARTS IMPACTED (%) (BY DOLLAR VALUE)	0.0	10.0	25.0	40.0	65.0	70.0	70.0	70.0	70.0	70.0

TABLE H7. INPUT DATA FOR CASH FLOW ANALYSIS -- IMPACT OF DEMONSTRATION CPPP ON MEDIUM SIZE COMPANY WITH FAIR PART SIMILARITY

YEAR	HARDWARE ($K)	ESTABLISH DATA FILES ($K)	TRAIN PERSONNEL ($K)	TEST SYSTEM ($K)	COMPUTER CHARGES & PROGRAM MAINTENANCE ($K)	UPDATING DATA FILES ($K)	PERCENTAGE OF PARTS IMPACTED (%)	PROCESS PLANNING SAVINGS ($K)	TOOLING SAVINGS ($K)	DIRECT LABOR SAVINGS ($K)	MATERIAL SAVINGS ($K)	SCRAP & REWORK COST SAVINGS ($K)	WIPI SAVINGS ($K)	DEPRECIATION ($K)	INVESTMENT TAX CREDIT ($K)	CASH FLOW BEFORE TAXES & DEPRECIATION ($K)	CASH FLOW AFTER TAXES & DEPRECIATION ($K)	CUMULATIVE PRESENT VALUE AFTER TAXES & DEPRECIATION ($K)
1	33.	30.	6.	10.	0.	0.	0.	0.	0.	0.	0.	0.	0.	6.	2.	-81.	-53.	-51.
2	10.	30.	6.	10.	43.	18.	10.	20.	3.	10.	5.	2.	7.	8.	1.	-72.	-38.	-84.
3	10.	0.	0.	0.	43.	36.	25.	50.	9.	25.	11.	5.	18.	9.	1.	26.	14.	-73.
4	0.	0.	0.	0.	43.	36.	40.	80.	14.	40.	18.	7.	29.	8.	0.	107.	59.	-30.
5	0.	0.	0.	0.	43.	36.	65.	130.	23.	65.	29.	12.	47.	7.	0.	225.	120.	48.
6	0.	0.	0.	0.	43.	36.	70.	140.	24.	70.	31.	13.	50.	6.	0.	248.	132.	126.
7	0.	0.	0.	0.	43.	36.	70.	140.	24.	70.	31.	13.	50.	5.	0.	248.	131.	196.
8	0.	0.	0.	0.	43.	36.	70.	140.	24.	70.	31.	13.	50.	4.	0.	248.	131.	260.
9	0.	0.	0.	0.	43.	36.	70.	140.	24.	70.	31.	13.	50.	3.	0.	248.	130.	318.
10	0.	0.	0.	0.	43.	36.	70.	140.	24.	70.	31.	13.	50.	2.	0.	248.	130.	370.
TOTALS	53.	60.	12.	20.	405.	306.		980.	171.	490.	220.	88.	353.	54.	4.	1443.	733.	

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 2.17
YEARS TO PAYBACK = 4.4
RETURN ON INVESTMENT = 33.3

FOR 10% ANNUAL DISCOUNT FACTOR BEFORETAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 2.27
YEARS TO PAYBACK = 4.4
RETURN ON INVESTMENT = 60.6

TABLE H8. CASH FLOW ANALYSIS -- IMPACT OF DEMONSTRATION CPPP ON MEDIUM SIZE COMPANY WITH FAIR PART SIMILARITY

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO : 2.17
YEARS TO PAYBACK : 4.4
RETURN ON INVESTMENT : 33.3

	CHANGE	.. NET CHANGES IN ... BCR	YTP	ROI
	******	*****	*****	*****
PERCENT OF PARTS IMPACTED	-10%	-0.21	0.27	-6.67
	10%	0.21	-0.20	6.33
PERCENT PROCESS PLANNING SAVINGS	-10%	-0.09	0.10	-2.70
	10%	0.09	-0.09	2.70
PERCENT TOOLING SAVINGS	-10%	-0.02	0.02	-0.48
	10%	0.02	-0.02	0.48
PERCENT LABOR SAVINGS	-10%	-0.04	0.03	-1.33
	10%	0.04	-0.03	1.43
PERCENT MATERIAL SAVINGS	-10%	-0.02	0.02	-0.63
	10%	0.02	-0.02	0.63
PERCENT SCRAP & REWORK SAVINGS	-10%	-0.01	0.01	-0.16
	10%	0.01	-0.01	0.32
PERCENT WIPI SAVINGS	-10%	-0.03	0.04	-0.93
	10%	0.03	-0.03	0.93
IMPLEMENTATION COSTS (HARDWARE, ESTABLISH FILES, TEST, TRAIN)	-10%	0.06	-0.10	3.63
	10%	-0.06	0.10	-3.09
RECURRING COSTS (COMPUTER CHARGES, MAINTENANCE, UPDATING FILES)	-10%	0.16	-0.13	3.17
	10%	-0.14	0.14	-3.02
VALUE OF MACHINED PARTS	-10%	-0.18	0.22	-3.33
	10%	0.18	-0.18	3.49
VALUE OF WIPI	-10%	-0.03	0.04	-0.93
	10%	0.03	-0.03	0.93
ORIGINAL PERCENT PROCESS PLANNING COSTS	-10%	-0.08	0.10	-2.62
	10%	0.08	-0.09	2.70
ORIGINAL PERCENT TOOLING COSTS	-10%	-0.00	0.00	-0.08
	10%	0.00	-0.00	0.16
ORIGINAL PERCENT LABOR COSTS	-10%	-0.01	0.01	-0.32
	10%	0.01	-0.01	0.32
ORIGINAL PERCENT MATERIAL COSTS	-10%	0.01	-0.01	0.32
	10%	-0.01	0.01	-0.16
ORIGINAL PERCENT SCRAP AND REWORK COSTS	-10%	-0.00	0.00	0.30
	10%	0.00	-0.00	0.16
ORIGINAL OTHER OTHER COSTS (OVERHEAD, FEE, ETC.)	-10%	0.18	-0.18	3.49
	10%	-0.18	0.22	-3.33

TABLE H9. SENSITIVITY ANALYSIS -- IMPACT OF DEMONSTRATION CPPP ON MEDIUM SIZE COMPANY WITH FAIR PART SIMILARITY

ANNUAL VALUE OF PARTS ($K) : 10000.0 ANNUAL VALUE OF WIPI ($K) : 6000.0

CURRENT COST COMPONENTS....

PROCESS PLANNING	: 3.0%	TOOLING	: 7.0%
DIRECT LABOR	: 20.0%	MATERIAL	: 15.0%
SCRAP & REWORK	: 3.0%	OVERHEAD, FEE, ETC	: 30.0%

POTENTIAL SAVINGS FOR THIS CASE....

PROCESS PLANNING	: 80.0%	TOOLING	: 15.0%
DIRECT LABOR	: 10.0%	MATERIAL	: [illegible].0%
SCRAP & REWORK	: 10.0%	WIPI	: 4.0%

YEARLY INPUT....

YEAR	1	2	3	4	5	6	7	8	9	10
HARDWARE COSTS ($K)	33.0	10.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ESTABLISH DATA FILES ($K)	60.0	80.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRAIN PERSONNEL ($K)	20.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TEST SYSTEM ($K)	0.0	40.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COMPUTER CHARGES & MAINTENANCE ($K)	0.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0
UPDATE DATA FILES ($K)	0.0	30.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
PERCENT OF PARTS IMPACTED (%) (BY DOLLAR VALUE)	0.0	5.0	20.0	35.0	60.0	70.0	70.0	70.0	70.0	70.0

TABLE H10. INPUT DATA FOR CASH FLOW ANALYSIS -- IMPACT OF ADVANCED CPPP ON MEDIUM SIZE COMPANY WITH FAIR PART SIMILARITY

YEAR	HARDWARE ($K)	ESTABLISH DATA FILES ($K)	TRAIN PERSONNEL ($K)	TEST SYSTEM ($K)	COMPUTER CHARGES & PROGRAM MAINTENANCE ($K)	UPDATING DATA FILES ($K)	PERCENTAGE OF PARTS IMPACTED (%)	PROCESS PLANNING SAVINGS ($K)	TOOLING SAVINGS ($K)	DIRECT LABOR SAVINGS ($K)	MATERIAL SAVINGS ($K)	SCRAP & REWORK COST SAVINGS ($K)	WIPI SAVINGS ($K)	DEPRECIATION ($K)	INVESTMENT TAX CREDIT ($K)	CASH FLOW BEFORE TAXES & DEPRECIATION ($K)	CASH FLOW AFTER TAXES & DEPRECIATION ($K)	CUMULATIVE PRESENT VALUE AFTER TAXES & DEPRECIATION ($K)
1	33.	60.	20.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	6.	2.	-113.	-71.	-68.
2	10.	80.	20.	40.	90.	30.	3.	20.	3.	10.	2.	2.	4.	8.	1.	-227.	-119.	-171.
3	10.	60.	0.	20.	90.	60.	20.	80.	21.	40.	9.	6.	14.	9.	1.	-70.	-36.	-199.
4	0.	0.	0.	0.	90.	60.	33.	140.	37.	70.	16.	10.	23.	8.	0.	148.	81.	-141.
5	0.	0.	0.	0.	90.	60.	60.	240.	63.	120.	27.	18.	43.	7.	0.	361.	191.	-17.
6	0.	0.	0.	0.	90.	60.	70.	280.	73.	140.	31.	21.	50.	6.	0.	446.	235.	122.
7	0.	0.	0.	0.	90.	60.	70.	280.	73.	140.	31.	21.	50.	5.	0.	446.	234.	248.
8	0.	0.	0.	0.	90.	60.	70.	280.	73.	140.	31.	21.	50.	4.	0.	446.	234.	362.
9	0.	0.	0.	0.	90.	60.	70.	280.	73.	140.	31.	21.	50.	3.	0.	446.	233.	466.
10	0.	0.	0.	0.	90.	60.	70.	280.	73.	140.	31.	21.	50.	2.	0.	446.	233.	560.
TOTALS	33.	200.	40.	60.	810.	510.		1880.	493.	940.	211.	141.	338.	34.	4.	2329.	1213.	

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 1.93
YEARS TO PAYBACK = 5.1
RETURN ON INVESTMENT = 44.7

FOR 10% ANNUAL DISCOUNT FACTOR BEFORETAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 1.98
YEARS TO PAYBACK = 5.1
RETURN ON INVESTMENT = 46.6

TABLE H11. CASH FLOW ANALYSIS -- IMPACT OF ADVANCED CPPP ON MEDIUM SIZE COMPANY WITH FAIR PART SIMILARITY

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FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 1.93
YEARS TO PAYBACK = 3.1
RETURN ON INVESTMENT = 44.7

	CHANGE	.. NET CHANGES IN ... BCR	YTP	ROI
	******	*****	*****	*****
PERCENT OF PARTS IMPACTED	-10%	-0.19	0.33	-3.79
	10%	0.19	-0.27	3.33
PERCENT PROCESS PLANNING SAVINGS	-10%	-0.09	0.14	-2.70
	10%	0.09	-0.13	2.70
PERCENT TOOLING SAVINGS	-10%	-0.02	0.04	-0.63
	10%	0.02	-0.03	0.79
PERCENT LABOR SAVINGS	-10%	-0.04	0.07	-1.27
	10%	0.04	-0.06	1.43
PERCENT MATERIAL SAVINGS	-10%	-0.01	0.02	-0.24
	10%	0.01	-0.01	0.32
PERCENT SCRAP & REWORK SAVINGS	-10%	-0.01	0.01	-0.16
	10%	0.01	-0.01	0.24
PERCENT WIPI SAVINGS	-10%	-0.02	0.02	-0.48
	10%	0.02	-0.02	0.48
IMPLEMENTATION COSTS (HARDWARE, ESTABLISH FILES, TEST, TRAIN)	-10%	0.06	-0.12	2.94
	10%	-0.05	0.12	-2.34
RECURRING COSTS (COMPUTER CHARGES, MAINTENANCE, UPDATING FILES)	-10%	0.14	-0.16	3.02
	10%	-0.12	0.17	-2.86
VALUE OF MACHINED PARTS	-10%	-0.17	0.30	-3.32
	10%	0.17	-0.24	3.08
VALUE OF WIPI	-10%	-0.02	0.02	-0.48
	10%	0.02	-0.02	0.48
ORIGINAL PERCENT PROCESS PLANNING COSTS	-10%	-0.08	0.13	-2.34
	10%	0.08	-0.12	2.34
ORIGINAL PERCENT TOOLING COSTS	-10%	-0.01	0.02	-0.32
	10%	0.01	-0.02	0.40
ORIGINAL PERCENT LABOR COSTS	-10%	-0.01	0.02	-0.32
	10%	0.01	-0.02	0.48
ORIGINAL PERCENT MATERIAL COSTS	-10%	0.02	-0.03	0.63
	10%	-0.02	0.03	-0.43
ORIGINAL PERCENT SCRAP AND REWORK COSTS	-10%	-0.00	0.00	0.00
	10%	0.00	-0.00	0.08
ORIGINAL OTHER OTHER COSTS (OVERHEAD, FEE, ETC.)	-10%	0.17	-0.24	3.08
	10%	-0.17	0.30	-3.32

TABLE H12. SENSITIVITY ANALYSIS -- IMPACT OF ADVANCED CPPP ON MEDIUM SIZE COMPANY WITH FAIR PART SIMILARITY

ANNUAL VALUE OF PARTS ($K) = 3000.0   ANNUAL VALUE OF VIPI ($K) = 2500.0

CURRENT COST COMPONENTS....

PROCESS PLANNING	= 4.0%	TOOLING	= 7.0%
DIRECT LABOR	= 27.0%	MATERIAL	= 13.0%
SCRAP & REWORK	= 2.0%	OVERHEAD, FEE, ETC	= 43.0%

POTENTIAL SAVINGS FOR THIS CASE....

PROCESS PLANNING	= 40.0%	TOOLING	= 3.0%
DIRECT LABOR	= 3.0%	MATERIAL	= 3.0%
SCRAP & REWORK	= 6.0%	VIPI	= 4.0%

YEARLY INPUT....

YEAR	1	2	3	4	5	6	7	8	9	10
HARDWARE COSTS ($K)	23.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ESTABLISH DATA FILES ($K)	20.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRAIN PERSONNEL ($K)	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TEST SYSTEM ($K)	10.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COMPUTER CHARGES & MAINTENANCE ($K)	6.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
UPDATE DATA FILES ($K)	0.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
PERCENT OF PARTS IMPACTED (%) (BY DOLLAR VALUE)	0.0	10.0	25.0	40.0	65.0	90.0	90.0	90.0	90.0	90.0

TABLE H13. INPUT DATA FOR CASH FLOW ANALYSIS -- IMPACT OF DEMONSTRATION CPPP ON SMALL COMPANY WITH HIGH PART SIMILARITY

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YEAR	HARDWARE ($K)	ESTABLISH DATA FILES ($K)	TRAIN PERSONNEL ($K)	TEST SYSTEM ($K)	COMPUTER CHARGES & PROGRAM MAINTENANCE ($K)	UPDATING DATA FILES ($K)	PERCENTAGE OF PARTS IMPACTED (%)	PROCESS PLANNING SAVINGS ($K)	TOOLING SAVINGS ($K)	DIRECT LABOR SAVINGS ($K)	MATERIAL SAVINGS ($K)	SCRAP & REWORK COST SAVINGS ($K)	WIPI SAVINGS ($K)	DEPRECIATION ($K)	INVESTMENT TAX CREDIT ($K)	CASH FLOW BEFORE TAXES & DEPRECIATION ($K)	CASH FLOW AFTER TAXES & DEPRECIATION ($K)	CUMULATIVE PRESENT VALUE AFTER TAXES & DEPRECIATION ($K)
1	23.	20.	6.	10.	6.	0.	0.	0.	0.	0.	0.	0.	0.	3.	2.	-67.	-43.	-41.
2	10.	20.	0.	10.	12.	10.	16.	8.	2.	7.	2.	1.	3.	6.	1.	-40.	-22.	-60.
3	0.	0.	0.	0.	12.	10.	23.	20.	4.	17.	6.	2.	8.	3.	0.	34.	20.	-44.
4	0.	0.	0.	0.	12.	10.	40.	32.	7.	27.	9.	2.	12.	3.	0.	67.	37.	-17.
5	0.	0.	0.	0.	12.	10.	63.	52.	11.	44.	13.	4.	19.	4.	0.	123.	66.	26.
6	0.	0.	0.	0.	12.	10.	90.	72.	16.	61.	20.	3.	27.	3.	0.	179.	93.	82.
7	0.	0.	0.	0.	12.	10.	90.	72.	16.	61.	20.	3.	27.	3.	0.	179.	94.	133.
8	0.	0.	0.	0.	12.	10.	90.	72.	16.	61.	20.	3.	27.	2.	0.	179.	94.	179.
9	0.	0.	0.	0.	12.	10.	90.	72.	16.	61.	20.	3.	27.	1.	0.	179.	94.	220.
10	0.	0.	0.	0.	12.	10.	90.	72.	16.	61.	20.	3.	27.	1.	0.	179.	94.	258.
TOTALS	33.	40.	6.	20.	114.	90.		472.	103.	398.	133.	33.	177.	33.	2.	1014.	329.	

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 2.99
YEARS TO PAYBACK = 4.4
RETURN ON INVESTMENT = 34.3

FOR 10% ANNUAL DISCOUNT FACTOR BEFORETAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 3.28
YEARS TO PAYBACK = 4.4
RETURN ON INVESTMENT = 39.2

TABLE H14. CASH FLOW ANALYSIS -- IMPACT OF DEMONSTRATION CPPP ON SMALL COMPANY WITH HIGH PART SIMILARITY

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 2.99
YEARS TO PAYBACK = 4.4
RETURN ON INVESTMENT = 34.3

	CHANGE	.. NET CHANGES IN ... BCR	YTP	ROI
	******	*****	*****	*****
PERCENT OF PARTS IMPACTED	-10%	-0.29	0.23	-4.84
	10%	0.29	-0.18	4.68
PERCENT PROCESS PLANNING SAVINGS........	-10%	-0.10	0.07	-1.67
	10%	0.10	-0.07	1.67
PERCENT TOOLING SAVINGS	-10%	-0.02	0.02	-0.40
	10%	0.02	-0.02	0.40
PERCENT LABOR SAVINGS	-10%	-0.09	0.06	-1.43
	10%	0.09	-0.06	1.43
PERCENT MATERIAL SAVINGS........	-10%	-0.03	0.02	-0.48
	10%	0.03	-0.02	0.48
PERCENT SCRAP & REWORK SAVINGS........	-10%	-0.01	0.01	-0.08
	10%	0.01	-0.01	0.16
PERCENT WIP SAVINGS........	-10%	-0.04	0.03	-0.63
	10%	0.04	-0.03	0.63
IMPLEMENTATION COSTS (HARDWARE, ESTABLISH FILES, TEST, TRAIN)	-10%	0.14	-0.12	3.49
	10%	-0.13	0.12	-3.02
RECURRING COSTS (COMPUTER CHARGES, MAINTENANCE, UPDATING FILES) ..	-10%	0.16	-0.08	1.31
	10%	-0.14	0.08	-1.43
VALUE OF MACHINED PARTS	-10%	-0.23	0.19	-4.21
	10%	0.23	-0.16	4.03
VALUE OF WIP	-10%	-0.04	0.03	-0.63
	10%	0.04	-0.03	0.63
ORIGINAL PERCENT PROCESS PLANNING COSTS	-10%	-0.10	0.07	-1.39
	10%	0.10	-0.06	1.39
ORIGINAL PERCENT TOOLING COSTS........	-10%	-0.01	0.00	-0.08
	10%	0.01	-0.00	0.08
ORIGINAL PERCENT LABOR COSTS........	-10%	-0.03	0.02	-0.40
	10%	0.03	-0.02	0.48
ORIGINAL PERCENT MATERIAL COSTS	-10%	0.01	-0.01	0.16
	10%	-0.01	0.01	-0.16
ORIGINAL PERCENT SCRAP AND REWORK COSTS	-10%	-0.00	0.00	0.00
	10%	0.00	-0.00	0.08
ORIGINAL OTHER OTHER COSTS (OVERHEAD, FEE, ETC.)........	-10%	0.20	-0.13	3.33
	10%	-0.20	0.13	-3.41

TABLE H15. SENSITIVITY ANALYSIS -- IMPACT OF DEMONSTRATION CPPP ON SMALL COMPANY WITH HIGH PART SIMILARITY

ANNUAL VALUE OF PARTS ($K) = 3000.0 ANNUAL VALUE OF WIPI ($K) = 2500.0

CURRENT COST COMPONENTS....

PROCESS PLANNING	= 4.0%	TOOLING	= 7.0%
DIRECT LABOR	= 27.0%	MATERIAL	= 13.0%
SCRAP & REWORK	= 2.0%	OVERHEAD, FEE, ETC	= 43.0%

POTENTIAL SAVINGS FOR THIS CASE....

PROCESS PLANNING	= 80.0%	TOOLING	= 15.0%
DIRECT LABOR	= 10.0%	MATERIAL	= 3.0%
SCRAP & REWORK	= 10.0%	WIPI	= 4.0%

YEARLY INPUT....

YEAR	1	2	3	4	5	6	7	8	9	10
HARDWARE COSTS ($K)	25.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ESTABLISH DATA FILES ($K)	40.0	60.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TRAIN PERSONNEL ($K)	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TEST SYSTEM ($K)	0.0	20.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
COMPUTER CHARGES & MAINTENANCE ($K)	0.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
UPDATE DATA FILES ($K)	0.0	20.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
PERCENT OF PARTS IMPACTED (%) (BY DOLLAR VALUE)	0.0	5.0	20.0	35.0	60.0	80.0	90.0	90.0	90.0	90.0

TABLE H16. INPUT DATA FOR CASH FLOW ANALYSIS -- IMPACT OF ADVANCED CPPP ON SMALL COMPANY WITH HIGH PART SIMILARITY

YEAR	HARDWARE ($K)	ESTABLISH DATA FILES ($K)	TRAIN PERSONNEL ($K)	TEST SYSTEM ($K)	COMPUTER CHARGES & PROGRAM MAINTENANCE ($K)	UPDATING DATA FILES ($K)	PERCENTAGE OF PARTS IMPACTED (%)	PROCESS PLANNING SAVINGS ($K)	TOOLING SAVINGS ($K)	DIRECT LABOR SAVINGS ($K)	MATERIAL SAVINGS ($K)	SCRAP & REWORK COST SAVINGS ($K)	WIPI SAVINGS ($K)	DEPRECIATION ($K)	INVESTMENT TAX CREDIT ($K)	CASH FLOW BEFORE TAXES & DEPRECIATION ($K)	CASH FLOW AFTER TAXES & DEPRECIATION ($K)	CUMULATIVE PRESENT VALUE AFTER TAXES & DEPRECIATION ($K)
1	23.	40.	20.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.	2.	-83.	-32.	-30.
2	10.	60.	0.	20.	30.	20.	5.	8.	3.	7.	1.	1.	2.	6.	1.	-119.	-63.	-103.
3	0.	40.	0.	10.	30.	40.	20.	32.	10.	27.	5.	2.	6.	5.	0.	-38.	-17.	-118.
4	0.	0.	0.	0.	30.	40.	35.	56.	18.	47.	8.	3.	10.	5.	0.	73.	40.	-89.
5	0.	0.	0.	0.	30.	40.	60.	96.	31.	81.	13.	6.	18.	4.	0.	176.	93.	-29.
6	0.	0.	0.	0.	30.	40.	80.	128.	42.	108.	18.	8.	24.	3.	0.	258.	136.	32.
7	0.	0.	0.	0.	30.	40.	90.	144.	47.	121.	20.	9.	27.	3.	0.	299.	137.	136.
8	0.	0.	0.	0.	30.	40.	90.	144.	47.	121.	20.	9.	27.	2.	0.	299.	136.	213.
9	0.	0.	0.	0.	30.	40.	90.	144.	47.	121.	20.	9.	27.	1.	0.	299.	136.	282.
10	0.	0.	0.	0.	30.	40.	90.	144.	47.	121.	20.	9.	27.	1.	0.	299.	136.	343.
TOTALS	33.	140.	20.	30.	270.	340.		896.	294.	736.	126.	36.	168.	33.	2.	1461.	762.	

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 2.12
YEARS TO PAYBACK = 3.4
RETURN ON INVESTMENT = 43.1

FOR 10% ANNUAL DISCOUNT FACTOR BEFORETAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 2.18
YEARS TO PAYBACK = 3.4
RETURN ON INVESTMENT = 44.8

TABLE H17. CASH FLOW ANALYSIS -- IMPACT OF ADVANCED CPPP ON SMALL COMPANY WITH HIGH PART SIMILARITY

FOR 10% ANNUAL DISCOUNT FACTOR AFTERTAXES AND DEPRECIATION....
BENEFIT-TO-COST RATIO = 2.12
YEARS TO PAYBACK = 3.4
RETURN ON INVESTMENT = 43.1

		.. NET CHANGES IN ...		
	CHANGE	BCR	YTP	ROI
	******	*****	*****	*****
PERCENT OF PARTS IMPACTED	-10%	-0.21	0.31	-4.92
	10%	0.21	-0.24	4.60
PERCENT PROCESS PLANNING SAVINGS..................................	-10%	-0.08	0.11	-1.90
	10%	0.08	-0.10	1.82
PERCENT TOOLING SAVINGS	-10%	-0.03	0.03	-0.63
	10%	0.03	-0.03	0.36
PERCENT LABOR SAVINGS	-10%	-0.07	0.09	-1.39
	10%	0.07	-0.08	1.31
PERCENT MATERIAL SAVINGS..	-10%	-0.01	0.01	-0.24
	10%	0.01	-0.01	0.24
PERCENT SCRAP & REWORK SAVINGS....................................	-10%	-0.01	0.01	-0.16
	10%	0.01	-0.01	0.08
PERCENT WIPI SAVINGS..	-10%	-0.02	0.02	-0.40
	10%	0.02	-0.02	0.32
IMPLEMENTATION COSTS (HARDWARE, ESTABLISH FILES, TEST, TRAIN)	-10%	0.08	-0.13	2.86
	10%	-0.07	0.13	-2.34
RECURRING COSTS (COMPUTER CHARGES, MAINTENANCE, UPDATING FILES) ..	-10%	0.14	-0.13	2.06
	10%	-0.12	0.14	-2.06
VALUE OF MACHINED PARTS	-10%	-0.19	0.28	-4.32
	10%	0.19	-0.22	4.28
VALUE OF WIPI	-10%	-0.02	0.02	-0.40
	10%	0.02	-0.02	0.32
ORIGINAL PERCENT PROCESS PLANNING COSTS	-10%	-0.08	0.10	-1.82
	10%	0.08	-0.09	1.67
ORIGINAL PERCENT TOOLING COSTS....................................	-10%	-0.01	0.02	-0.32
	10%	0.01	-0.02	0.32
ORIGINAL PERCENT LABOR COSTS......................................	-10%	-0.02	0.03	-0.36
	10%	0.02	-0.03	0.48
ORIGINAL PERCENT MATERIAL COSTS	-10%	0.02	-0.03	0.48
	10%	-0.02	0.03	-0.48
ORIGINAL PERCENT SCRAP AND REWORK COSTS	-10%	-0.00	0.00	-0.08
	10%	0.00	-0.00	0.00
ORIGINAL OTHER OTHER COSTS (OVERHEAD, FEE, ETC.)..................	-10%	0.16	-0.19	3.49
	10%	-0.16	0.22	-3.73

TABLE H18. SENSITIVITY ANALYSIS -- IMPACT OF ADVANCED CPPP ON SMALL COMPANY WITH HIGH PART SIMILARITY

TABLE H19. PROJECTED SAVINGS IN ARMY MISSILE PROCUREMENT FROM DEMONSTRATION CPPP.

			Projected Savings ($Thousands)						
Fiscal Year	Total Procurement ($Millions)	Cylindrical Parts Procurement ($Millions)	Implement in FY79 (1%)	Implement in FY80 (1%)	Implement in FY81 (3%)	Implement in FY82 (5%)	Implement in FY83 (5%)	Total Savings For Year	Discounted Total Savings For Year
78	657	65.7	0	0	0	0	0	0	0
79	723	72.3	-5.7	0	0	0	0	- 5.7	- 4.9
80	795	79.5	-4.0	-6.3	0	0	0	-10.3	- 8.1
81	874	87.4	4.9	-4.4	-20.7	0	0	-20.2	-14.5
82	962	96.2	12.1	5.4	-14.4	-38.0	0	-34.9	-22.8
83	1058	105.8	25.0	13.3	17.8	-26.5	-41.8	-12.2	- 7.2
84	1164	116.4	36.7	27.5	44.0	32.6	-29.1	111.7	60.1
85	1280	128.0	40.3	40.3	90.6	80.6	35.8	287.6	140.6
86	1408	140.8	44.4	44.4	133.1	166.1	88.7	476.7	212.1
87	1549	154.9	48.8	48.8	146.4	244.0	182.8	670.8	271.7
							Total	1463.5	627.0

TABLE H20. PROJECTED SAVINGS IN ARMY MISSILE PROCUREMENT FROM ADVANCED CPPP.

			Projected Savings ($Thousands)						
Fiscal Year	Total Procurement ($Millions)	Cylindrical Parts Procurement ($Millions)	Implement in FY79 (1%)	Implement in FY80 (1%)	Implement in FY81 (3%)	Implement in FY82 (5%)	Implement in FY83 (5%)	Total Savings For Year	Discounted Total Savings For Year
78	657	65.7	0	0	0	0	0	0	0
79	723	72.3	- 7.6	0	0	0	0	- 7.6	- 6.6
80	795	79.5	-13.4	- 8.3	0	0	0	-21.7	-17.1
81	874	87.4	- 2.1	-14.8	-27.5	0	0	-44.4	-31.8
82	962	96.2	15.9	- 2.3	-48.8	-50.5	0	-85.7	-55.9
83	1058	105.8	38.5	17.5	- 7.6	-89.4	-55.5	-96.5	-57.1
84	1164	116.4	57.5	42.4	57.6	-14.0	-98.4	45.1	24.3
85	1280	128.0	69.8	63.2	139.8	105.6	-15.4	363.0	177.5
86	1408	140.8	76.7	76.7	208.7	256.3	116.2	734.6	326.9
87	1549	154.9	84.4	84.4	253.3	382.6	281.9	1087.4	440.4
							Total	1974.2	800.6

TABLE H21. PROJECTED SAVINGS IN TOTAL ARMY PROCUREMENT FROM DEMONSTRATION CPPP.

			Projected Savings ($Thousands)						
Fiscal Year	Total Procurement ($Millions)	Cylindrical Parts Procurement ($Millions)	Implement in FY79 (1%)	Implement in FY80 (1%)	Implement in FY81 (3%)	Implement in FY82 (5%)	Implement in FY83 (5%)	Total Savings For Year	Discounted Total Savings For Year
78	6,342	317.1	0	0	0	0	0	0	0
79	6,976	348.8	-27.6	0	0	0	0	- 27.6	- 23.9
80	7,674	383.7	-19.2	-30.3	0	0	0	- 49.5	- 39.0
81	8,441	422.1	23.6	-21.1	-100.0	0	0	- 97.5	- 69.9
82	9,285	464.3	58.5	26.0	- 69.6	-183.4	0	-168.5	-109.9
83	10,214	510.7	120.5	64.3	85.8	-127.7	-201.7	- 58.8	- 34.8
84	11,235	561.8	177.0	132.6	212.3	157.3	-140.4	538.8	289.9
85	12,359	618.0	194.7	194.7	437.5	389.3	173.0	1389.2	679.3
86	13,595	679.8	214.1	214.1	642.4	802.1	428.2	2300.9	1023.9
87	14,954	747.7	235.5	235.5	706.6	1177.6	882.3	3237.5	1311.2
							Total	7064.5	3026.8

TABLE H22. PROJECTED SAVINGS IN TOTAL ARMY PROCUREMENT FROM ADVANCED CPPP.

			Projected Savings ($Thousands)						
Fiscal Year	Total Procurement ($Millions)	Cylindrical Parts Procurement ($Millions)	Implement in FY79 (1%)	Implement in FY80 (1%)	Implement in FY81 (3%)	Implement in FY82 (5%)	Implement in FY83 (5%)	Total Savings For Year	Discounted Total Savings For Year
78	6,342	317.1	0	0	0	0	0	0	0
79	6,976	348.8	-36.6	0	0	0	0	- 36.6	- 31.7
80	7,674	383.7	-64.8	-40.3	0	0	0	-105.1	- 82.8
81	8,441	422.1	-10.1	-71.3	-132.9	0	0	-214.3	-153.7
82	9,285	464.3	76.6	-11.1	-235.4	-243.7	0	-413.6	-269.7
83	10,214	510.7	185.9	84.3	- 36.8	-431.5	-268.1	-466.2	-276.0
84	11,235	561.8	277.5	204.5	278.1	- 67.4	-474.7	218.0	117.3
85	12,359	618.0	336.8	305.3	674.8	509.8	- 74.2	1752.5	857.0
86	13,595	679.8	370.5	370.5	1007.4	1237.1	560.8	3546.3	1578.1
87	14,954	747.7	407.5	407.5	1222.5	1846.8	1360.8	5245.1	2124.3
							Total	9526.1	3862.8

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TABLE H23. PROJECTED SAVINGS IN DEPARTMENT OF DEFENSE PROCUREMENT FROM DEMONSTRATION CPPP

Fiscal Year	Total Procurement ($Millions)	Cylindrical Parts Procurement ($Millions)	Projected Savings ($Thousands)						
			Implement in FY79 (1%)	Implement in FY80 (1%)	Implement in FY81 (3%)	Implement in FY82 (5%)	Implement in FY83 (5%)	Total Savings For Year	Discounted Total Savings For Year
78	35,143	1,757.2	0	0	0	0	0	0	0
79	38,657	1,932.9	-152.7	0	0	0	0	- 152.7	- 132.4
80	42,523	2,126.2	-106.3	-168.0	0	0	0	- 274.3	- 216.1
81	46,775	2,338.8	131.0	-116.9	-554.3	0	0	- 540.2	- 387.3
82	51,453	2,572.7	324.2	144.1	-385.9	-1016.2	0	- 933.8	- 608.8
83	56,598	2,829.9	667.9	356.6	475.4	- 707.5	-1117.8	- 325.4	- 192.6
84	62,258	3,112.9	980.6	734.6	1176.7	871.6	- 778.2	2,985.3	1,606.1
85	68,484	3,424.2	1078.6	1078.6	2424.3	2157.2	958.8	7,697.5	3,764.1
86	75,332	3.766.6	1186.5	1186.5	3559.4	4444.6	2373.0	12,750.0	5,673.8
87	82,865	4,143.3	1305.1	1305.1	3915.4	6525.6	4889.0	17,940.2	7,365.8
							Total	39,146.6	16,772.6

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TABLE H24. PROJECTED SAVINGS IN DEPARTMENT OF DEFENSE PROCUREMENT FROM ADVANCED CPPP

Fiscal Year	Total Procurement ($Millions)	Cylindrical Part Procurement ($Millions)	Projected Savings ($Thousands) Implement in FY79 (1%)	Implement in FY80 (1%)	Implement in FY81 (3%)	Implement in FY82 (5%)	Implement in FY83 (5%)	Total Savings For Year	Discounted Total Savings For Year
78	35,143	1,757.2	0	0	0	0	0	0	0
79	38,657	1,932.9	-202.9	0	0	0	0	- 202.9	- 175.9
80	42,523	2,126.2	-359.3	-223.2	0	0	0	- 582.5	- 459.0
81	46,775	2,338.8	- 56.1	-395.2	- 736.7	0	0	-1,188.0	- 851.8
82	51,453	2,572.7	424.5	- 61.7	-1304.3	-1350.6	0	-2,292.1	-1,494.4
83	56,598	2,829.9	1030.1	466.9	- 203.8	-2391.3	-1485.7	-2,583.8	-1,529.6
84	62,258	3,112.9	1537.8	1133.1	1540.9	- 373.5	-2630.4	1,207.9	649.9
85	68,484	3,424.2	1866.2	1691.6	3739.2	2825.0	- 410.9	9,711.1	4,748.7
86	75,332	3,766.6	2052.8	2052.8	5582.1	6855.2	3107.4	19,650.3	8,744.4
87	82,865	4,143.3	2258.1	2258.1	6774.2	10233.8	7540.7	29,064.9	11,771.3
							Total	52,784.9	21,403.6

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